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NAVAL POSTGRADUATE SCHOOL

Monterey, California

CONTRACTOR REPORT

CALIBRATION AND APPLICATION OF A COMBINATION TEMPERATURE-PNEUMATIC PROBE FOR VELOCITY AND ROTOR LOSS DISTRIBUTION MEASUREMENTS IN A COMPRESSOR

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Contractor Report

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Monterey, California 93940

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A description is given of the current design of a temperature-pneumatic probe used for radial flow field surveys in an axial compressor. The procedure used to calibrate the probe for variations in Mach number, pitch and yaw angles in a free jet is described and the procedure for representing the characteristics of the probe analytically as three polynomial surfaces, is given.

Verification of the calibration in steady flow and application of the probe to obtain radial surveys in a small axial compressor are also described. The procedures developed and reported here allow the probe to be used with automatic reduction of data by mini-computer without the need for iteration.

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1. INTRODUCTION

The probe reported here was designed to be used to determine the radial distribution of the time-averaged flow in a small, single-stage axial compressor (Figure 1). While the probe has more general application, the chosen geometry is the result of its first intended application.

The probe was designed to measure air flows in the range of Mach number from 0.3 to 0.7 with pitch angles expected in the range 0 to 15 degrees and stagnation temperatures from atmospheric to about 150°F (65°C). Static pressure would range from 0.6 to about 1.2 atmospheres.

The prototype of the present probe was built by Dodge and was reported in Ref 1. The first application of the earlier design to measure rotor losses and deviation angles was reported in Ref 2 and Ref 3. In Ref 3, errors in the earlier work were corrected and the method used to analytically represent the calibration of the probe was set out more clearly.

The design of the present probe departs only in detail from that of the prototype, for reasons which are given in Section 2. However, the method now used to represent the calibration of the probe is quite different and considered to be much improved over that reported in earlier references.

In the present report, the probe design is described in Section 2 and the analytical and experimental procedures used in its calibration are given in Section 3. Steady flow tests to

verify the calibration and compressor measurements are reported in Section 4 and conclusions are given in Section 5. The analytical basis for the pneumatic calibration representation is given in Appendix A. The computer programs, procedures and data files used in the calibration and verification are given in Appendix B.

2. PROBE DESCRIPTION

2.1. General Arrangement

The probe is designed to measure four pressures and one temperature. Figure 2 shows a drawing of the probe and a view is shown in Figure 3. Due to the symmetry of the probe about one plane through its (radial) axis, a balancing of the pressures at sensors P2 and P3 in Figure 3 by rotating the probe around the radial axis allows the yaw angle to be read against a vernier scale or recorded using a potentiometer read-out of the angular orientation. The pitch angle as well as the magnitude of the dimensionless velocity (or Mach number) at the probe tip are calculated using the pressure readings of the four sensors. The relationship of the pressures to Mach number and pitch angle must first be established by calibration. The stagnation temperature is needed in order to calculate the magnitude of the velocity from the dimensionless velocity or Mach number. The exposed fine-wire thermocouple sensor supported in the stagnation region formed by a glassy aluminum oxide insulator, gives an output which corresponds fairly closely to stagnation temperature. The departure from stagnation temperature, the recovery factor, must also be established by calibration.

2.2. Design Features

The probe was designed to have separate sensors to avoid the so-called "stem-effect" associated with cylindrical probes having surface sensors (Reference 4). The restricted axial gap

in the compressor (0.63") did not allow the use of a "goose-neck" conical probe. As was reported in Reference (2), the stem-effect was found to be negligible for the first probe geometry to within 0.25" of the wall. The probe was designed to be translated through a hole of 0.25 inches diameter. The sensors P1, P2 and P3 were placed at the same radial location and therefore similarly average the flow from the upstream rotor blade wakes. These sensors largely dictate the measurement of Mach number. The pressures P1 and P4 largely dictate the measurement of pitch. The sensor P4 was unavoidably displaced radially from the other three. However, since the pitch angle variation to be measured was rather small, and since the radial gradients in flow properties were small outside the wall boundary-layers, this necessity was easily accepted. It is also noted that when the probe is adjusted in yaw, the sensor P1 will indicate stagnation pressure very closely since the pitch angle is not expected to exceed 15°.

The radial separation of the temperature sensor was also easily accepted since the probe was to be translated in radial surveys and the physical displacement could be accounted for in the data reduction. The arrangement and the geometry of the temperature sensor were chosen so that a high recovery factor and sensitivity would be obtained and yet the element could be repaired easily in the event of a failure. The shape ground into the glassy insulator and the method of stringing the thermocouple wire were changed from those reported in References 1 and 3. In the new arrangement, a long length of

thermocouple wire is exposed on either side of the junction within the near-stagnation flow ahead of the insulator. This results in a higher recovery factor at all Mach numbers and a more easily controlled and repeatable geometry.

The tubes for sensors P2, P3 and P4 (Figure 3) were oriented at 55^{o} to the sensor P1 based on the known behavior of a straight cylindrical tube when pitched or yawed to the flow (Reference 1). An angle of about 55^{o} was required in order for the pressure at the sensor to decrease from stagnation to static pressure. In the earlier design (Reference 1) the centers of the sensors were arranged to be on the surface of a small sphere which, in effect, determined the spatial resolution of the probe. This is shown in Figure 4. Also in Figure 4 is shown the tip design of the present probe. The sensors were initially positioned such that the centers of the tubes were aligned in a plane, and were closer together than in the earlier design. Initial tests of the revised geometry resulted in the measurement of small differences between the pressure sensed at P2, P3 and P4, and that at P1. It was conjectured that the surrounding sensors were too nearly aligned with the flow induced over the central sensor and were therefore measuring close to stagnation pressure. The tips of the surrounding sensors were modified as shown in Figure 4 and pressure differences near to dynamic pressure were subsequently obtained.

3. CALIBRATION

3.1. Apparatus and Procedure

The probe was calibrated in a 4.25" diameter freejet exhausting to atmosphere. The apparatus shown in Figure 5 can be used to establish air flows to a Mach number of unity. Pitch angle can be set within a range of +45 to -45 degrees while the yaw angle can be set to any angle desired. In effecting angle changes the probe tip is rotated about its tip which remains at the same point on the center line of the jet.

The geometry for the tests and the instrumentation are shown in Figure 6. The speed of the flow was adjusted by monitoring the impact pressure using a water manometer board. The static pressure was taken to be the atmospheric pressure while the total pressure and temperature were measured in the air supply pipe immediately upstream of the nozzle. No difference in total pressure was detected in the flow between the sensor upstream of the nozzle to the core of the jet and hence the same total conditions (pressure and temperature) were assumed for the pipe and the jet core. Since the temperature of the supplied air fluctuated measurably due to ambient (coastal) variations, the difference between the total temperature in the pipe and the temperature detected by the combination probe was recorded differentially. A thermocouple probe having a fine-wire sensor similar to that of the combination probe was used at the upstream station. The absolute value of the temperature

in the supply air was measured using the same upstream thermocouple element referenced to ice point.

All pressures were converted to voltages using a Scanivalve and single calibrated transducer for which the reference pressure was atmospheric. The thermocouple voltage differences were recorded without amplification. Yaw angles were adjusted to a vernier scale and converted to voltage using a potentiometer. The pitch angle was set to a scale on the adjustable mount and recorded manually.

Pressure tubes P2 and P3 were connected to a U-tube manometer. The probe was aligned (in yaw) with the flow by balancing the two pressures. The pneumatically averaged value of the two pressures - designated P23 - was recorded and used in representing the calibration of the probe. All data were recorded and analyzed using the data acquisition system shown in Figure 7. The programs and organization of data files are given in Appendix B. Before beginning calibration tests, since the sensors for two pressures and the sensor for temperature were physically separated radially, the velocity distribution across the jet was examined. Figure 8 shows the velocity distribution obtained by probe measurement. It can be seen that for a core of approximately 3 inches in diameter the flow was uniform.

The procedure was as follows:

The required Mach number was established. Having allowed some 5 to 10 minutes for the flow to stabilize, the yaw angle of the probe at zero degrees of pitch was checked. With the probe aligned with the flow, P2 and P3 should be the same and

the angle read on the vernier scale should be zero. Any departure was corrected by adjusting the probe in the probe holder. The first pitch angle was set at -6° and a scan of the data was taken. The pitch angle was changed in increments of 2° up to an angle of $+18^{\circ}$, taking a data scan at each setting. A sample of the raw data output is shown in Table I.

After one survey over pitch angle, the probe was reset to zero pitch and zero yaw, the Mach number of the flow was changed and the procedure repeated. The range of Mach number from 0.3 to 0.7 was covered in increments of 0.1 or less.

3.2. Dimensionless Velocity - Pneumatic Calibration

The characteristics of the probe must be represented such that pressures and temperatures measured in a flow can be related to the pitch and yaw angles and the velocity magnitude. However, since the probe is always rotated to balance the pressures P2 and P3, the yaw angle can always be read directly. It is left therefore to establish the relationship for pitch angle and velocity magnitude in terms of the probe pressures and temperature for the special case of zero yaw.

Appendix A discusses the reduction of the four measured pressures to basically two coefficients:

$$\beta = \frac{P1 - P23}{P1} \tag{1}$$

and

$$\gamma = \frac{P1 - P4}{P1 - P23} , \tag{2}$$

where

$$\delta = \gamma \cdot \beta \qquad (3)$$

might be looked at as an alternate choice. These coefficients can be established using the pressure readings from the probe for any flow condition. The calibration gives a total of 104 different values for β, and corresponding values of γ and δ for 104 separate combinations of Mach number and pitch angle. The reduced data are given in Table II.

It can be argued (Appendix A), and it can be seen in the results that β represents largely a measurement of the Mach number and γ provides mainly a measurement of the pitch angle. However, if explicit relationships for the reduced velocity, X (defined by Equation A(3) using Equation A(1)), and the pitch angle, ϕ, in terms of β and γ can be obtained by representing the calibration data using monotonic mathematical functions, X or ϕ can then be determined uniquely for any given values of β and γ. The method involves using mathematical approximations of surfaces which represent the calibration data. In the way that data points which depend on just one variable can be approximated by a polynomial, X and ϕ are approximated as being polynomial functions of both β and γ. This leads to mathematical expressions for the calibration surfaces which are of the form:

$$X = \sum_{i=1}^{L} \left\{ \sum_{j=1}^{M} C_{ij} \beta^{(j-1)} \right\} \cdot \gamma^{(i-1)} \qquad (4)$$

and

$$\phi = \sum_{i=1}^{L} \{ \sum_{j=1}^{M} D_{ij} \beta^{(j-1)} \} \cdot \gamma^{(i-1)} \tag{5}$$

where C_{ij} and D_{ij} are coefficients which must be derived from the data.

Using the computer programs given in Reference 5, the surfaces represented by Equation (4) and Equation (5) were derived from the calibration data. Also derived and examined were the alternate surfaces obtained by electing to use the coefficients δ and γ instead of β and γ, related through Equation (3). The equations for the alternate surfaces are the following:

$$X = \sum_{i=1}^{L} \{ \sum_{j=1}^{M} C_{ij} \delta^{(j-1)} \} \cdot \gamma^{(i-1)} \tag{4a}$$

$$\phi = \sum_{i=1}^{L} \{ \sum_{j=1}^{M} D_{ij} \delta^{(j-1)} \} \cdot \gamma^{(i-1)} \tag{5a}$$

[It is noted that the representation achieved using Equation (4) and Equation (5) or Equation (4a) and Equation (5a) is similar to the earlier method of polynomial approximation described in Reference 3. However, in the method of Reference 3, the expression for X was implicit and an iterative technique was required to obtain X and ϕ from measured values of β and γ or δ and γ. The derivation of the polynomial coefficients using matrix operations makes possible the use of explicit relations for both X and ϕ.]

The choice of using Equation (4) and Equation (5) or Equation (4a) and Equation (5a) was made after an examination of the

relative accuracy of the two methods. Using the calibration data, for each given pair of values for δ and γ, X and ϕ were calculated using the coefficients determined in the two sets of equations. The calculated X was compared in each case to the actual value set in the calibration test and an error was defined as follows:

$$\varepsilon_X = \frac{X_0 - X_c}{X_0} \cdot 100 \qquad (6)$$

where X_0 is the actual value in the calibration test and X_c is the value calculated using the surface approximation equation. The error in X so defined is then a percentage deviation from the actual value. For the pitch angle, the error as a percentage is not meaningful (for example, when $\phi \approx 0$). The error was defined as

$$\varepsilon_\phi = \phi_0 - \phi_c \qquad (7)$$

where ϕ_0 is the actual value set in the calibration test and ϕ_c is the value of the pitch angle (in degrees) calculated using the derived surface approximation equation. From an examination of the relative errors, the selection of using Equation (4a) and Equation (5a), rather that Equation (4) and Equation (5), was made.

The "surfaces" obtained by drawing straight lines between data points on a 3D plot of the test data are shown in Figures 9 and 10 together with the "surfaces" obtained by joining the points calculated using Equation (4a) and Equation (5a). The magnitude of the errors shown graphically in Figure 9 are given in Table

III, together with the values of the coefficients used in the approximation equations.

In the method given in Reference 5 the order of the polynomial approximation can be changed between 1 and 6 for the dependence on δ and between 1 and 6 for the dependence on γ, independently. The plots of Figure 9 and the corresponding errors in Table III are for the selection which gave the best results in that the averaged error was least in the range of velocity and pitch angle anticipated in the probe application. As indicated in Table III, the range expected in Mach number is from .3 to .7 and in pitch angle, from 0.0° to 12.0°. The maximum error within this range was +1.109% in X and 0.417° in pitch angle, while the average error was -0.061% in X and -0.016° in pitch angle.

3.3. Temperature Recovery Calibration

Since the probe was to be used to measure losses, requiring an evaluation of velocity magnitude rather than simply the Mach number or dimensionless velocity, it was also required to measure the local flow total temperature.

Even in a flow in which the angle of the velocity vector is uniform and known it is difficult to design a probe which will measure true stagnation temperature to an acceptable accuracy when the Mach number is in the higher subsonic range. In the present design, advantage was taken of the fine wire sensor being small and in poor thermal contact with a glassy insulator. While the "temperature recovery" of the probe was

expected to be comparatively high, a calibration to establish the value of the temperature recovery factor was required nevertheless. In the calibration test a voltage was recorded as the result of the temperature difference between the combination probe sensor and the total temperature sensor in the pipe upstream of the jet nozzle. (The relation between the output in millivolts and the temperature in degrees Fahrenheit for a single sensor referenced to ice point is given in Appendix C.) The output of the upstream probe was also recorded with reference to ice point. As the upstream probe was always in a low Mach number flow (less than 0.2), it was assumed that its output corresponded to the total temperature of the flow. The voltage difference between the upstream probe and the combination probe was then a measure of the departure of the combination probe temperature from the stagnation temperature.

The "temperature recovery factor", R, is defined as

$$R = \frac{T_p - T_s}{T_t - T_s} \tag{8}$$

where T_p is the temperature indicated by the probe, T_s is the static temperature, and T_t is the total temperature of the flow.

Since Equation (8) contains the static as well as the total temperature, one of the two can be expressed in terms of the other and the Mach number or dimensionless velocity. Using Equation A(4) and rearranging, Equation (8) becomes

$$T_t = \frac{T_p}{1 - X^2 + X^2 R} \tag{9}$$

where X is the velocity made dimensionless by dividing by the

"limiting" or "stagnation" velocity defined by Equation A(1). Since X is established by applying the calibration in Section 3.2 to the pneumatic measurements, it is only necessary to know R in order to determine T_t from the temperature T_p indicated by the probe. From the physical arrangement of the probe it is evident that the thermocouple junction is differently exposed to the flow at different yaw and pitch angles, and the Mach number is known to have a major influence on the temperature recovery factor. However, since the yaw angle is always adjusted to zero and the pitch angle and Mach number depend uniquely on the measured values of δ and γ, the recovery factor can also be approximated as a surface of values depending on δ and γ; thus

$$R = \sum_{i=1}^{L} \left\{ \sum_{j=1}^{M} E_{ij} \delta^{(j-1)} \right\} \cdot \gamma^{(i-1)} \tag{10}$$

The calibration surface obtained from the calibration test data is shown in Figure 11. The coefficients evaluated from the data and the resulting percentage errors in the approximation are given in Table IV. It can be seen that errors of less than 0.8% occur within the range of measurements.

4. APPLICATION

4.1. Verification of the Calibration

Before using the probe for compressor measurements, the probe was mounted on the free jet again to obtain data with which to verify the calibration. The probe was aligned with the flow but Mach number and pitch angle were set remotely and unknown to the operator. A total of 12 separate conditions with various combinations of pitch angle and Mach number were set. The results are shown in Table V. The largest error was found to be 0.55° in pitch and 0.7% in Mach number.

4.2. Compressor Measurements

The probe can be used in any flow for which conditions are within the ranges of pitch angle and Mach number covered in the calibration. Its intended application, however, was to determine the flow between blade rows in the compressor shown in Figure 1. In the compressor annulus, large radial gradients might be expected to occur (under some operating conditions) in pitch angle, yaw angle and Mach number, so that account had to be taken of the physical separation (0.08 inches) of the probe pressure and temperature sensors in the radial direction. This could be done easily since the probe was to be used in radial surveys and spatial interpolation could be used in reducing the data.

The procedure adopted was to first interpolate the raw data obtained for the radial distribution of the temperature

rise. The data, in the form of the differential voltage between the probe thermocouple sensor and a similar reference thermocouple sensor in the compressor inlet, was interpolated using an overlapping quadratic technique to obtain the differential voltage at the locations at which pneumatic data were taken. The temperature recovery factor was evaluated at each location using Equation 10 using the locally measured values of δ and γ. The probe temperature T_p was obtained using the measured value of the reference temperature, the interpolated differential voltage and the thermocouple calibration given in Appendix C. The stagnation temperature was obtained using Equation 9.

An example of the radial distribution of the temperature rise across the rotor measured in this way is shown in Figure 12. The corresponding data are given in Table VI.

The uncertainties in the measurements made in the compressor flow field are similar to the uncertainties present in the probe calibration measurements, since the instrumentation used was the same. However, the calibration was carried out in a uniform steady flow whereas the flow field at the rotor exit is periodic, therefore unsteady. The possible error resulting from unsteady effects is discussed in Appendix D. For the data presented here the possible error due to unsteady effects is negligible. A further evaluation of unsteady effects must be made for measurements made at higher rotational speeds and flow Mach numbers.

5. CONCLUSIONS

The combination probe and the method used to represent its calibration which are described in this report represent significant improvements over the prototype probe design and calibration method reported earlier. The pneumatic characteristics of the probe were improved as a result of modifications to the tip geometry. This allowed the pneumatic characteristics to be well represented by a polynomial surface approximation.

The polynomial surface approximation technique used to represent both the pneumatic and temperature characteristics of the probe provides a simpler and more accurate technique than was previously available. Most importantly, however, it allows the calibration to be applied directly, allowing Mach number and pitch angle to be calculated from pressure measurements without the need for iteration.

The improved probe and procedures were well proven in tests carried out in the compressor.

SCANIVALVE # 2

PORT	VOLTAGE(UNCORR.)
2	-0.000002
4	0.001355
6	0.000766
8	0.000128
10	-0.000240
12	0.000765

SCANNER # 1

CHAN	DATA
25	0.003009

SCANNER # 2

CHAN	DATA
6	0.002009
7	0.002427
8	-0.000004

SCANIVALVE # 2

RAW DATA WITH VOLTAGE CORRECTED TO PRESSURES(IN.H2O)

PA-PA	PCAL-PA**	P1-PA	P23-PA	P4-PA	PK-PA	P BARO (INCH HG)
-0.2000	135.500 **	76.6000	12.8000	-24.0000	76.500	30.094
0.0000	135.600 **	77.1000	13.6000	-19.0000	76.600	30.084
-0.4000	135.400 **	76.5000	13.9000	-14.6000	75.900	30.167
-0.2000	135.400 **	76.6000	13.9000	-9.5000	76.200	30.111
-0.4000	135.400 **	76.6000	13.6000	-4.4000	76.300	30.080
-0.4000	135.400 **	76.3000	13.6000	1.3000	76.400	30.131
-0.6000	135.200 **	76.5000	13.3000	6.1000	76.300	30.113
-0.3000	135.400 **	76.7000	13.2000	11.2000	76.500	30.061
-0.7000	135.100 **	76.1000	12.6000	15.6000	75.900	30.046
-0.6000	135.100 **	76.1000	12.4000	20.2000	76.400	30.108
-0.7000	135.000 **	76.2000	12.1000	23.9000	76.000	30.094
-0.7000	135.100 **	76.1000	12.1000	27.5000	76.500	30.142
-0.7000	135.100 **	75.6000	12.0000	30.2000	75.700	30.165

RAW DATA CORRECTED TO READINGS IN MILLIVOLTS

T TUNNEL	T PIPE(IP)	D T(PIPE-COMB)	** PHI
2.0087	2.4266	-0.0037	-6.0000
2.0092	2.4283	-0.0085	-4.0000
2.0063	2.4258	-0.0041	-2.0000
2.0083	2.4288	-0.0052	0.0000
2.0098	2.4290	-0.0022	2.0000
2.0072	2.4273	-0.0044	4.0000
2.0101	2.4301	-0.0090	6.0000
2.0128	2.4312	-0.0076	8.0000
2.0119	2.4304	-0.0082	10.0000
2.0080	2.4277	-0.0056	12.0000
2.0089	2.4294	-0.0109	14.0000
2.0091	2.4283	-0.0073	16.0000
2.0105	2.4284	-0.0143	18.0000

DATA STORED IN YPRB50

Table I. Example of Calibration Raw Data and Stored Data

Beta	Gamma	Delta	X vel	Machno.	Phi	T Tunnel	T ref pipe	Tcomborobe	Rec.Fac
.053425	1.521552	.081288	.133252	.300642	-6.000000	96.246826	98.163193	98.081116	[illegible]
.052952	1.460870	.077356	.132766	.299525	-4.000000	96.163483	98.204239	99.092934	.998678
.052722	1.397380	.073672	.132033	.297843	-2.000000	96.285034	98.189590	98.107498	.991564
.052722	1.318777	.069528	.132766	.299525	0.000000	96.390561	98.107498	97.972626	.986290
.052479	1.254386	.065829	.132766	.299525	2.000000	96.236404	98.171997	97.966751	.979139
.052722	1.170305	.061700	.132522	.298966	4.000000	96.257248	98.242355	98.066467	.982059
.052709	1.100437	.058003	.132522	.298966	6.000000	96.271133	98.236481	98.154404	.991628
.053363	1.025862	.054743	.132522	.298966	8.000000	96.267670	98.300980	98.239426	.993722
.052940	.952174	.050408	.132278	.294404	10.000000	96.305878	98.163193	97.957962	.979986
.053194	.874459	.046516	.132766	.299525	12.000000	96.264191	98.204239	98.107913	.980037
.053860	.803412	.043272	.133009	.300083	14.000000	96.201691	98.230621	98.259949	1.002970
.054078	.753191	.040731	.133252	.300642	16.000000	96.232941	98.095779	97.937454	.984023
.053885	.700855	.037766	.132766	.299525	18.000000	96.208618	98.125092	97.931580	.980330

Beta	Gamma	Delta	X vel	Machno.	Phi	T Tunnel	T ref pipe	Tcomborobe	Rec.Fac
.089321	1.535627	.137164	.176351	.400612	-6.000000	96.990005	98.913498	95.592697	.908953
.088185	1.487562	.131181	.176867	.401822	-4.000000	97.167114	99.083435	95.968597	.821900
.088166	1.420398	.125231	.176867	.401822	-2.000000	97.365067	99.270950	94.390930	.721963
.088366	1.359802	.120160	.176179	.400208	0.000000	97.479660	99.402740	94.296875	.705939
.088347	1.277915	.112900	.176523	.401015	2.000000	97.712341	99.546265	95.016922	.740226
.088785	1.192716	.105008	.176523	.401015	4.000000	97.854721	99.745392	94.894009	.675989
.088605	1.103961	.097816	.176695	.401419	6.000000	98.004059	99.967941	94.623123	.694283
.089462	1.012255	.090559	.176867	.401822	8.000000	98.160324	100.099700	95.378281	.730528
.089662	.951100	.085278	.176523	.401015	10.000000	98.361755	100.330960	95.069809	.699677
.089521	.872547	.078112	.176695	.401419	12.000000	98.600322	100.597310	96.649658	.774453
.089980	.809756	.072862	.176006	.399803	14.000000	98.677780	100.693860	95.636749	.708847
.089760	.762836	.068472	.177038	.402224	16.000000	98.966019	100.386980	96.226959	.734920
.090630	.709443	.064303	.176006	.399803	18.000000	99.341080	101.305340	94.573166	.612831

Beta	Gamma	Delta	X vel	Machno.	Phi	T Tunnel	T ref pipe	Tcomborobe	Rec.Fac
.120498	1.560976	.188094	.207722	.474838	-6.000000	101.869280	103.920810	103.564580	.985360
.118843	1.507067	.179105	.208549	.476815	-4.000000	101.949140	103.827360	103.666780	.993452
.117164	1.448028	.169656	.207860	.475169	-2.000000	101.883160	103.941240	103.856570	.996525
.117559	1.375000	.161643	.207998	.475498	0.000000	101.997770	103.973360	103.754360	.991025
.118164	1.289521	.152375	.207860	.475169	2.000000	102.011660	103.976260	103.789410	.992332
.118189	1.197158	.141490	.207998	.475498	4.000000	102.091520	104.090130	103.914950	.992822
.118818	1.116608	.132673	.207860	.475169	6.000000	102.161000	104.040500	103.827360	.991254
.119053	1.029982	.122623	.207584	.474508	8.000000	102.150560	104.063840	103.891620	.992914
.119658	.954386	.114200	.208136	.475827	10.000000	102.202650	104.125150	103.841960	.988412
.120338	.877836	.105637	.207998	.475498	12.000000	102.216550	104.087200	103.900380	.992344
.120918	.812500	.098246	.208412	.476486	14.000000	102.157520	104.139740	104.005460	.994520
.120918	.760417	.091948	.207860	.475169	16.000000	102.275590	104.116410	103.777740	.986105
.120309	.713787	.085932	.208274	.476157	18.000000	102.250220	104.119310	103.827360	.988069

Beta	Gamma	Delta	X vel	Machno.	Phi	T Tunnel	T ref pipe	Tcomborobe	Rec.Fac
.131612	1.576802	.207526	.219159	.502265	-6.000000	102.372820	104.256500	104.148510	.996016
.130912	1.513346	.198121	.219031	.501957	-4.000000	102.390200	104.306120	104.058000	.990835
.129110	1.455272	.187890	.218646	.501030	-2.000000	102.389470	104.233140	104.113460	.995563
.129343	1.373206	.177615	.218774	.501339	0.000000	102.358930	104.320710	104.168950	.994381
.129908	1.285714	.167025	.219159	.502265	2.000000	102.411030	104.326550	104.233140	.996554
.129370	1.196172	.154748	.219287	.502573	4.000000	102.320720	104.276930	104.148510	.995267
.130294	1.113924	.145137	.219415	.502880	6.000000	102.421450	104.358660	104.095960	.990331
.130939	1.031496	.135063	.219287	.502573	8.000000	102.515210	104.390760	104.168950	.991827
.130993	.952756	.124805	.218903	.501648	10.000000	102.483950	104.367420	104.128050	.991149
.131433	.877551	.115339	.219543	.504188	12.000000	102.348510	104.288600	104.125150	.993990
.132204	.815913	.107867	.219159	.502265	14.000000	102.379780	104.338240	104.020870	.988262
.132025	.759375	.100256	.219798	.503803	16.000000	102.386720	104.306120	104.093050	.992184
.131335	.713837	.093752	.218774	.501339	18.000000	102.435330	104.309050	103.891620	.984545

Table II. Complete Set of Reduced Calibration Data

Beta	Gamma	Delta	X vel	Mnchno.	Phi	T Tunnel	T ref pipe	Tcombprobe	Rec.Fac
.153507	1.595331	.244894	.240619	.554328	-6.000000	102.793050	104.682590	104.533770	.995448
.151745	1.538058	.233393	.240285	.553511	-4.000000	103.084750	105.015200	104.334320	.994455
.150401	1.473545	.221622	.240397	.553783	-2.000000	103.140300	105.158140	105.050200	.996695
.149744	1.394422	.208807	.240619	.554329	0.000000	103.296590	105.070630	104.799560	.991439
.150291	1.300662	.195478	.240508	.554055	2.000000	103.282700	105.149380	104.822660	.990086
.150719	1.208719	.182177	.240174	.553238	4.000000	103.275740	105.073530	104.816800	.992124
.151715	1.119424	.169833	.240731	.554600	6.000000	103.286160	105.286480	105.108550	.994548
.152329	1.043081	.158892	.240397	.553783	8.000000	103.293120	105.268970	105.143540	.996161
.152451	.959530	.146281	.240285	.553511	10.000000	103.442460	105.341890	105.155210	.994281
.153247	.884416	.135534	.239950	.552692	12.000000	103.244510	105.315640	105.076460	.992652
.153537	.822309	.126255	.240397	.553783	14.000000	103.414670	105.336060	105.228150	.996697
.153507	.767834	.117868	.240285	.553510	16.000000	103.432020	105.403140	105.190230	.993478
.153123	.714844	.109459	.239839	.552419	18.000000	103.494540	105.394390	105.058960	.989686

Beta	Gamma	Delta	X vel	Mnchno.	Phi	T Tunnel	T ref pipe	Tcombprobe	Rec.Fac
.173006	1.609131	.278389	.258473	.598294	-6.000000	103.852230	105.840530	105.677250	.995681
.171937	1.550336	.266560	.258869	.599277	-4.000000	104.015460	106.012530	105.788060	.994082
.168925	1.484055	.250694	.258770	.599031	-2.000000	104.126570	106.167020	105.960050	.994541
.167226	1.411968	.236117	.257677	.596320	0.000000	104.140470	106.164110	106.041690	.996743
.168445	1.315420	.221577	.258572	.598540	2.000000	104.189090	106.172050	106.062100	.997074
.169023	1.217540	.205792	.258473	.598294	4.000000	104.334950	106.324420	106.263210	.998382
.170305	1.126554	.191857	.257876	.596814	6.000000	104.345370	106.295270	106.164110	.994517
.170497	1.040533	.178772	.257677	.596320	8.000000	104.328000	106.382710	106.094150	.992327
.170469	.947232	.164083	.257876	.596814	10.000000	104.432190	106.414760	106.190340	.994042
.171751	.890134	.152081	.258572	.598539	12.000000	104.470380	106.478080	106.175780	.991997
.172328	.823464	.141906	.258770	.599031	14.000000	104.459980	106.473050	106.274870	.994775
.172361	.773184	.133267	.258671	.598786	16.000000	104.567630	106.615830	106.560470	.998540
.172235	.717002	.123493	.257976	.597061	18.000000	104.612700	106.674120	106.338990	.991114

Beta	Gamma	Delta	X vel	Mnchno.	Phi	T Tunnel	T ref pipe	Tcombprobe	Rec.Fac
.194665	1.641706	.319582	.279619	.651225	-6.000000	105.776150	107.836200	107.821620	.999672
.191932	1.583654	.303954	.279533	.651006	-4.000000	105.960270	107.914810	107.798360	.997376
.191324	1.506256	.288183	.279793	.651463	-2.000000	105.970630	108.034150	107.943920	.997971
.189419	1.427875	.270466	.279706	.651444	0.000000	106.203310	108.066180	107.874050	.995677
.191124	1.329150	.254032	.279880	.651883	2.000000	106.241520	108.156400	107.978840	.996010
.191159	1.232625	.235627	.278923	.649467	4.000000	106.335280	108.261180	107.958470	.993153
.190684	1.146035	.218531	.279359	.650566	6.000000	106.380430	108.406690	108.106900	.993242
.190860	1.058027	.201935	.278662	.648806	8.000000	106.488080	108.363040	108.185500	.995977
.192160	.973129	.186994	.278574	.649585	10.000000	106.581850	108.604570	108.415420	.995713
.192600	.897510	.172860	.279098	.649907	12.000000	106.585330	108.688950	108.403790	.993563
.193409	.835878	.161646	.279793	.651463	14.000000	106.620060	108.735470	108.432880	.993204
.193438	.779370	.150760	.278662	.648806	16.000000	106.734660	108.758760	108.496900	.994071
.194993	.732004	.142736	.280139	.652539	18.000000	106.866620	108.782040	108.520190	.994134

Beta	Gamma	Delta	X vel	Mnchno.	Phi	T Tunnel	T ref pipe	Tcombprobe	Rec.Fac
.217339	1.654221	.359526	.300115	.703508	-6.000000	107.561170	109.584760	109.483000	.998016
.213911	1.596867	.341588	.300573	.704686	-4.000000	107.762590	109.799910	109.683610	.997741
.210524	1.530151	.322133	.300420	.704294	-2.000000	107.877200	109.991760	110.032460	1.000791
.208658	1.444632	.301434	.299734	.702525	0.000000	107.773010	110.003390	109.849320	.996991
.212254	1.349627	.286464	.300420	.704294	2.000000	108.085570	110.317930	109.773740	.995253
.210802	1.247492	.262974	.299351	.701538	4.000000	108.148090	110.166150	109.924910	.995278
.210208	1.156040	.243009	.299734	.702525	6.000000	108.259200	110.247530	109.983050	.994838
.210208	1.072148	.225374	.299197	.701144	8.000000	108.172390	110.349240	110.087690	.994877
.210644	.981559	.206760	.299581	.702131	10.000000	108.460630	110.378300	110.177780	.996083
.212185	.901912	.191372	.300039	.703312	12.000000	108.530080	110.570080	110.320180	.995135
.212827	.839967	.178768	.300039	.703311	14.000000	108.648160	110.581700	110.360870	.995701
.214403	.781250	.167502	.299504	.701933	16.000000	108.651630	110.700820	110.384110	.993813
.214390	.724076	.155406	.299010	.702721	18.000000	108.880840	110.892560	110.642700	.995131

Table II (Cont'd). Complete Set of Reduced Calibration Data

COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FILE COEFOX::28

	1	2	3	4
1	.073424	3.193492	-3.328469	48.710213
2	.055790	-2.348127	-14.044533	-48.302086
3	-.157956	1.903296	14.359398	13.222536
4	.076260	-.838803	-2.848467	-1.069147
	1	2	3	4

ERRORS(%) AT EACH POINT

Mach # ↓ / Pitch # →	1	2	3	4	5	6	7	8	9	10	11	12	13
1	-1.123	-.634	-.502	.554	1.109	.882	.898	.081	.084	-.097	-.759	-.821	-.924
2	.110	.706	.446	-.129	.149	.014	.334	-.019	-.264	.100	-.303	.742	.172
3	-.291	.275	.401	.122	-.178	.038	-.207	-.351	-.278	-.485	-.248	-.093	.905
4	.039	-.508	-.220	-.401	-.371	.108	-.116	-.377	-.494	-.230	-.470	.347	.727
5	.138	-.075	.093	.351	.257	.179	.168	-.156	-.211	-.562	-.262	.083	.644
6	-.237	-.546	.136	.291	.398	.437	-.100	-.198	-.101	-.244	-.170	.105	.491
7	.350	.104	-.319	.214	-.095	-.121	.406	.165	-.332	-.250	-.119	-.193	.266
8	.027	-.134	.103	.202	-.705	-.197	.378	.298	.303	-.010	-.034	-.372	.391
	1	2	3	4	5	6	7	8	9	10	11	12	13

COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FILE COEFOP::28

	1	2	3	4
1	52.538452	126.896670	232.935610	1219.634300
2	-69.122833	-369.909970	-845.455930	-1152.339800
3	33.816833	370.705320	736.521000	-117.727780
4	-8.974613	-121.404030	-154.774540	186.470580
	1	2	3	4

ABSOLUTE ERRORS AT EACH POINT

Mach # ↓ / Pitch # →	1	2	3	4	5	6	7	8	9	10	11	12	13
1	-.170	-.094	.036	-.136	.166	-.012	.175	.190	.149	-.135	-.364	-.033	.139
2	-.328	.109	.090	.417	.314	-.032	.029	-.327	.008	-.278	-.251	.185	.298
3	-.238	-.009	.251	.265	.155	.005	.119	-.004	-.002	-.207	-.260	-.019	.314
4	.002	-.136	.168	-.018	-.117	-.143	-.035	-.030	-.093	-.257	-.195	-.109	.253
5	-.029	.049	.141	.080	-.107	-.115	-.090	.122	-.016	-.155	-.097	.061	.141
6	-.198	-.176	-.055	.125	-.088	-.156	-.105	.116	.074	-.101	-.186	.108	.061
7	.222	.270	-.036	.019	-.181	-.136	.099	.158	.053	-.054	.033	.126	.309
8	-.167	.004	.126	.010	-.107	-.104	.081	.278	.083	-.131	-.051	-.059	-.131
	1	2	3	4	5	6	7	8	9	10	11	12	13

TABLE III. Pneumatic Calibration Coefficients and Errors in Surface Approximation of Calibration Test Data

COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FILE COEFOR

	1	2	3	4	5	6
1	.967377	-.443312	-1.249723	37.673103	-191.830080	813.623660
2	.029453	1.236710	-1.544683	-41.071510	-43.770836	-339.013060
3	.040476	-1.567321	7.522579	28.097572	38.016373	-145.301360
4	-.119724	.257648	-1.990074	-8.393269	28.396744	-10.002936
5	.104485	-.078570	-3.395687	12.758770	2.119871	18.219982
6	-.035093	.251334	.301610	-4.679673	-3.011747	1.296416
	1	2	3	4	5	6

ERRORS(%) AT EACH POINT

Mach # Pitch # →

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	.047	-.049	.394	-.026	-.710	-.397	.561	.747	-.764	-.661	1.657	-.207	-.574
2	-.591	.084	.395	-.140	.013	.080	-.075	.105	-.326	.125	.418	-.345	-.047
3	.400	-.233	.221	.104	.436	.226	-.271	-.111	-.146	.200	-.303	.196	-.471
4	.236	.008	.188	-.331	-.446	-.215	.030	.188	.021	-.093	.392	.170	-.982
5	.016	-.232	-.164	.115	.222	.388	.195	-.245	-.076	-.253	.097	.560	-.050
6	.139	-.110	.022	-.070	.111	-.108	-.107	.123	.056	-.164	-.164	.001	.190
7	.009	-.100	.235	-.002	-.046	.069	.042	-.009	.050	-.076	.000	-.131	.117
	1	2	3	4	5	6	7	8	9	10	11	12	13

Table IV. Temperature Calibration Coefficients and Errors in Surface Approximation of Calibration Test Data

				Pitch Angle			Mach Number		
Point # [ ]	Beta [ ]	Gamma [ ]	Delta [ ]	Actual [°]	Calculated [°]	Error [°]	Actual [ ]	Calculated [ ]	Error [%]
1	.04203	1.36313	.05730	- 2.0	- 2.185	+0.185	.2578	.2579	-0.07
2	.06167	1.36059	.08390	- 2.0	- 1.946	-0.054	.3220	.3201	0.59
3	.06141	1.14552	.07035	5.0	5.299	+0.299	.3210	.3213	-0.09
4	.07789	1.15274	.08979	5.0	5.265	+0.265	.3660	.3684	-0.66
5	.08614	.97416	.08392	10.0	9.749	-0.251	.3840	.3866	-0.67
6	.08340	1.23467	.10297	3.0	2.787	-0.213	.3848	.3838	0.27
7	.08385	1.16711	.09786	5.0	4.889	-0.111	.3848	.3845	0.09
8	.09485	1.17783	.11172	5.0	4.681	-0.319	.4134	.4125	0.22
9	.09567	1.33638	.12785	0.0	- 0.425	+0.425	.4145	.4131	0.34
10	.11626	1.21533	.14129	4.0	3.822	+0.178	.4667	.4634	0.71
11	.12066	.91740	.11069	12.0	12.550	-0.550	.4678	.4681	-0.05
12	.14510	1.05626	.15327	8.0	8.419	-0.419	.5258	.52398	0.35

Table V. Probe Calibration Verification Test Results

Normalized Displacement	Yaw	Pitch Angle (Degrees)	Mach Number	$X=V/V_T$	T_{total} (2)	T_{total} (ref)	Velocity (ft/sec)
.092105	37.7	10.6	.36928	.16294	96.163651	70.670853	429.64
.155789	38.1	9.9	.37749	.16646	96.340683	72.337265	416.84
.217368	37.4	9.1	.36567	.16139	94.938721	71.385300	403.05
.271579	36.8	7.6	.35321	.15603	94.003922	70.343277	397.77
.321053	35.9	6.7	.34868	.15407	93.712097	69.687836	393.27
.365789	35.1	5.9	.34469	.15235	93.917160	70.194351	389.52
.423158	35.3	4.7	.34132	.15090	94.706573	70.760193	389.53
.472105	34.9	4.2	.34116	.15083	96.342072	72.694092	388.36
.518421	34.6	4.0	.33990	.15028	96.021194	73.021072	386.09
.589474	34.5	3.5	.33777	.14936	95.787674	73.347977	383.95
.658421	33.1	3.1	.33588	.14854	95.057907	72.694092	381.15
.727895	32.7	2.7	.33335	.14745	96.021820	73.615387	377.52
.797895	31.0	1.9	.33013	.14605	99.315994	76.256638	375.31
.850526	31.1	1.6	.32824	.14524	97.394363	74.239090	375.74
.896842	31.2	3.0	.32851	.14536	94.125595	71.623383	376.15
.947895	34.0	5.9	.31257	.13844	92.896500	71.385300	376.93

Table VI. Compressor Test Results

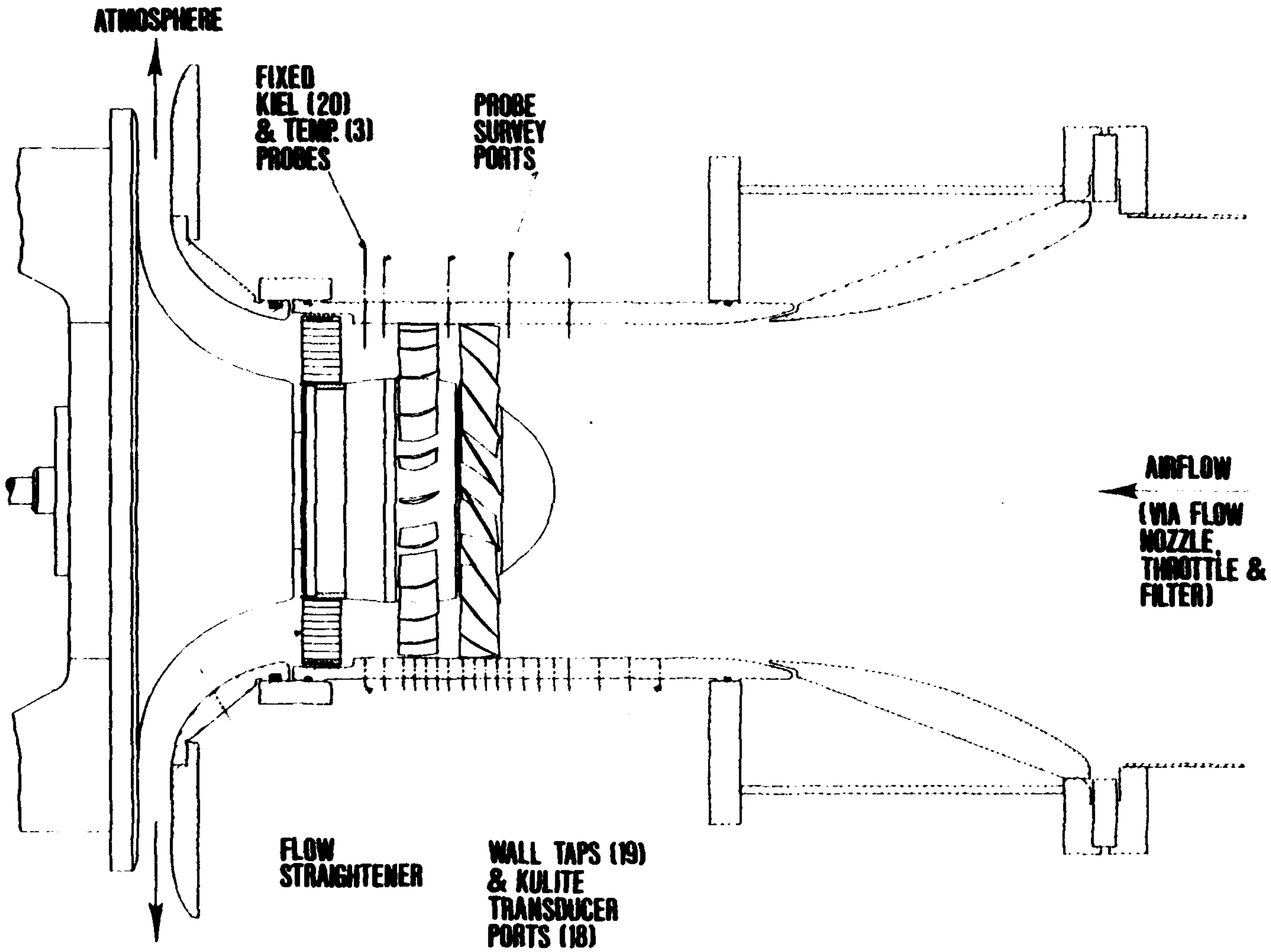


Figure 1. Transonic Compressor

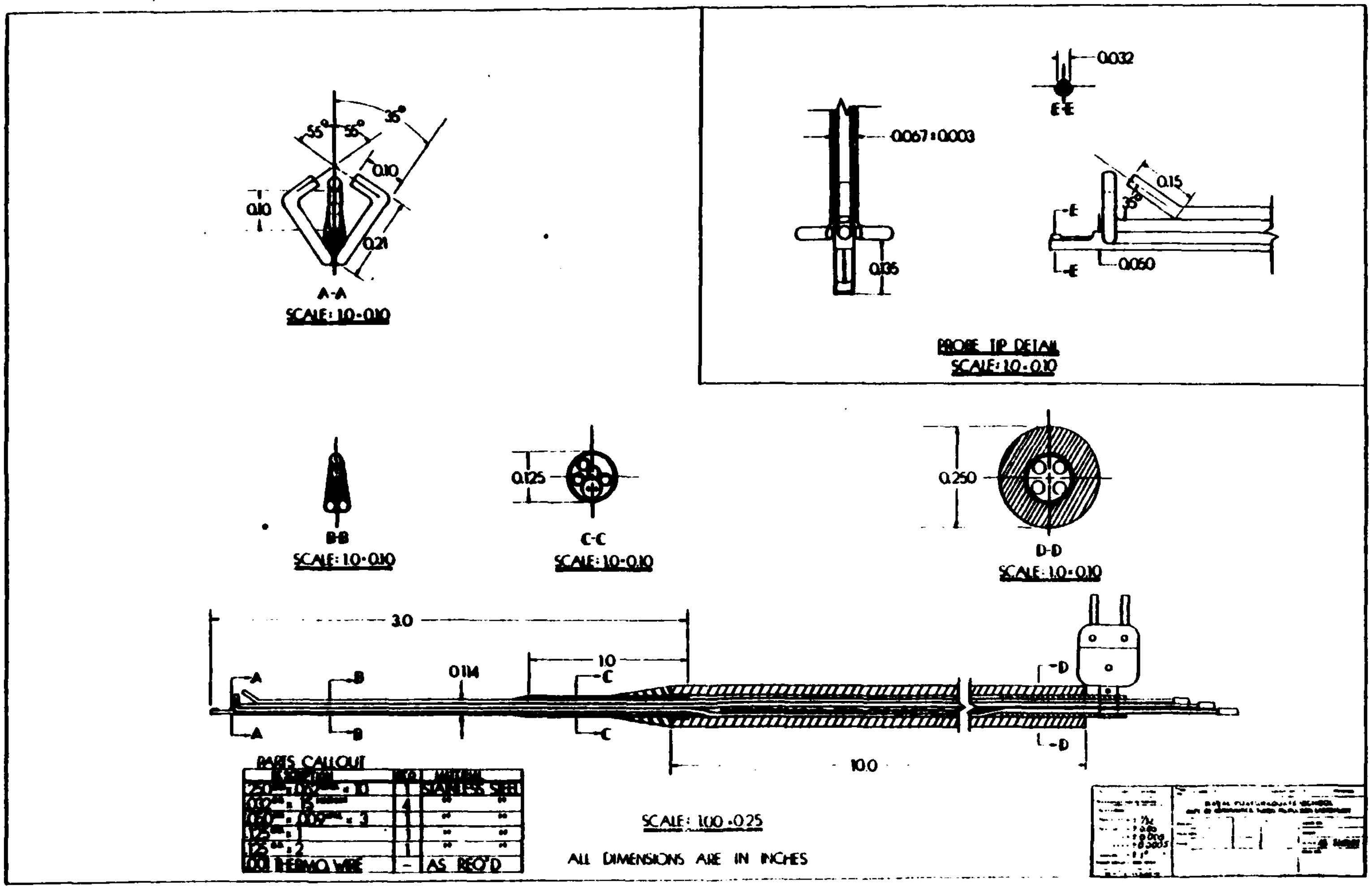
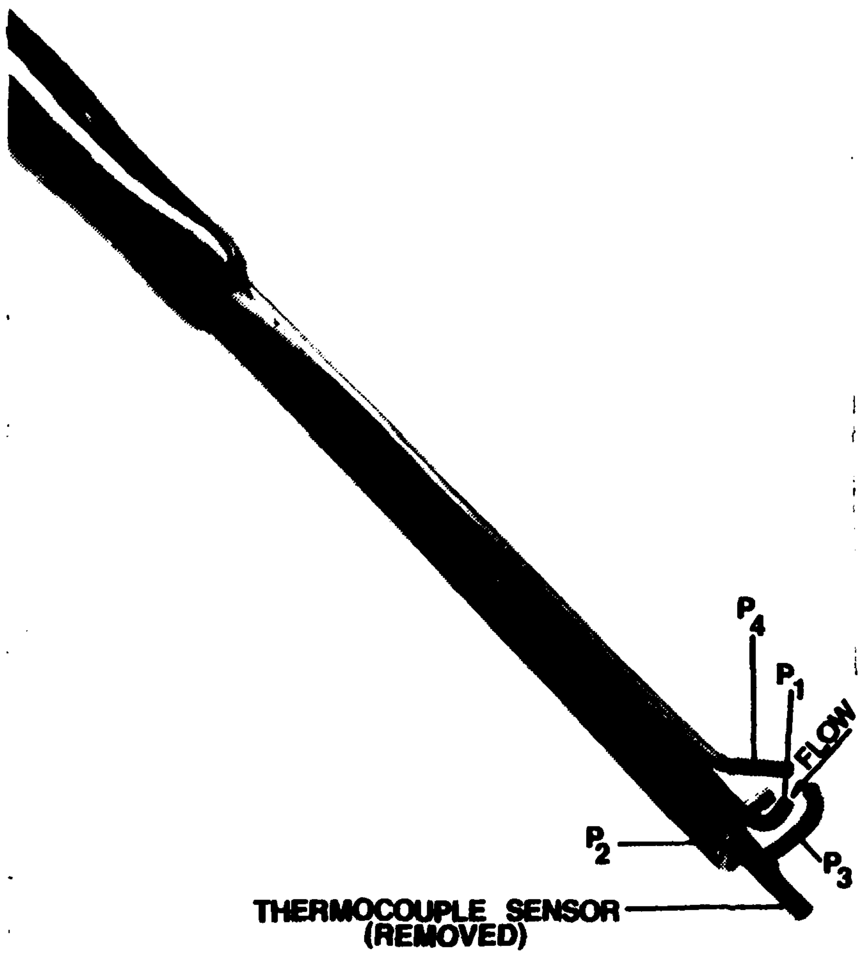
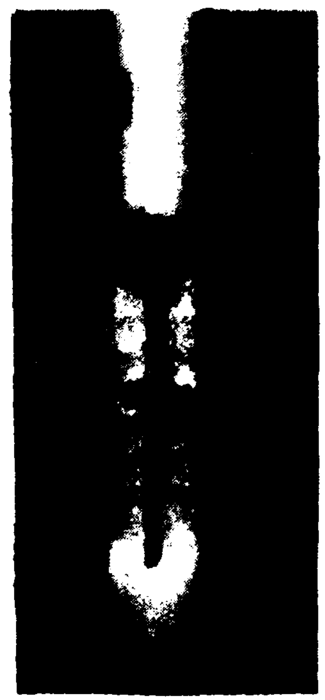


Figure 2. Geometry of the Combination Probe





Scale 20X

Figure 3. Views of the Combination Probe
(Left - With Thermocouple Sensor Removed. Right - Thermocouple Sensor)

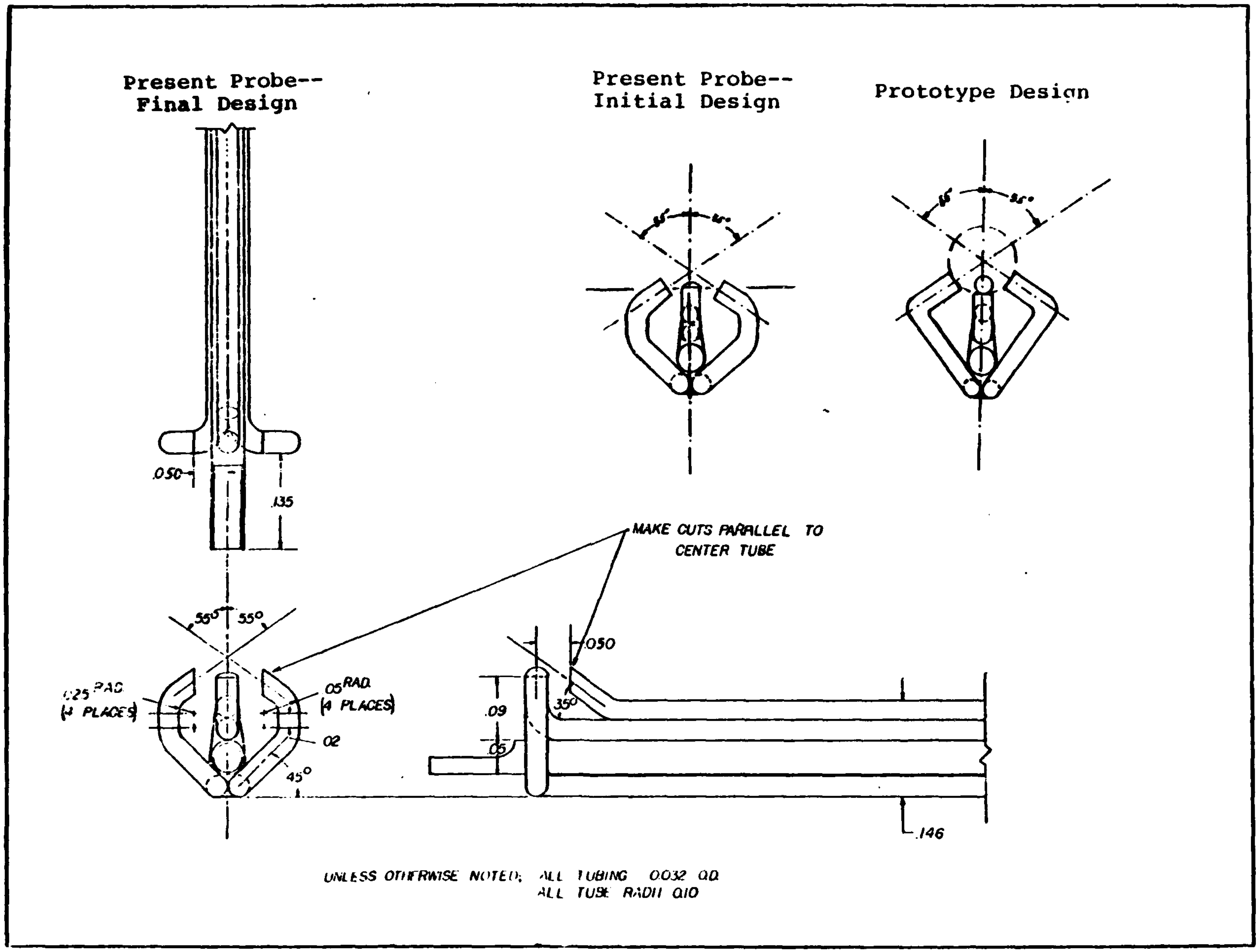
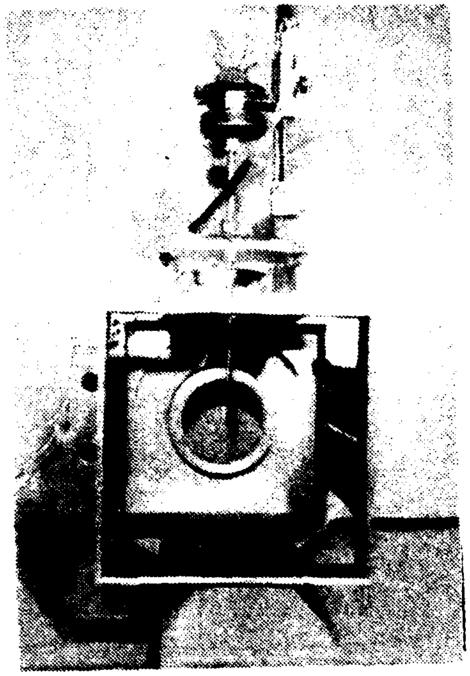
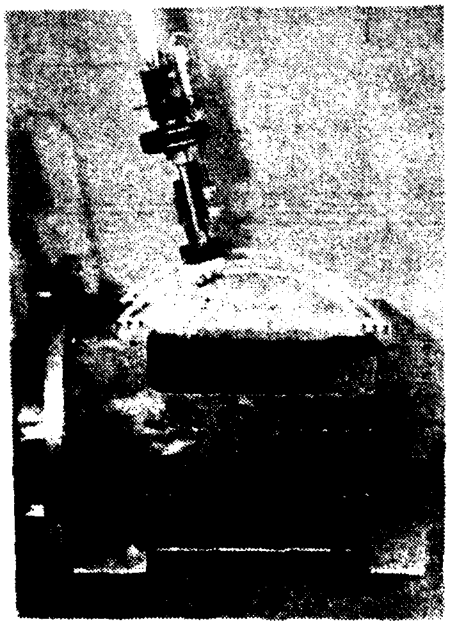


Figure 4. Tip Design Detail and Modifications



(a) End View



(b) Side View

Figure 5. Free-Jet Calibration Apparatus

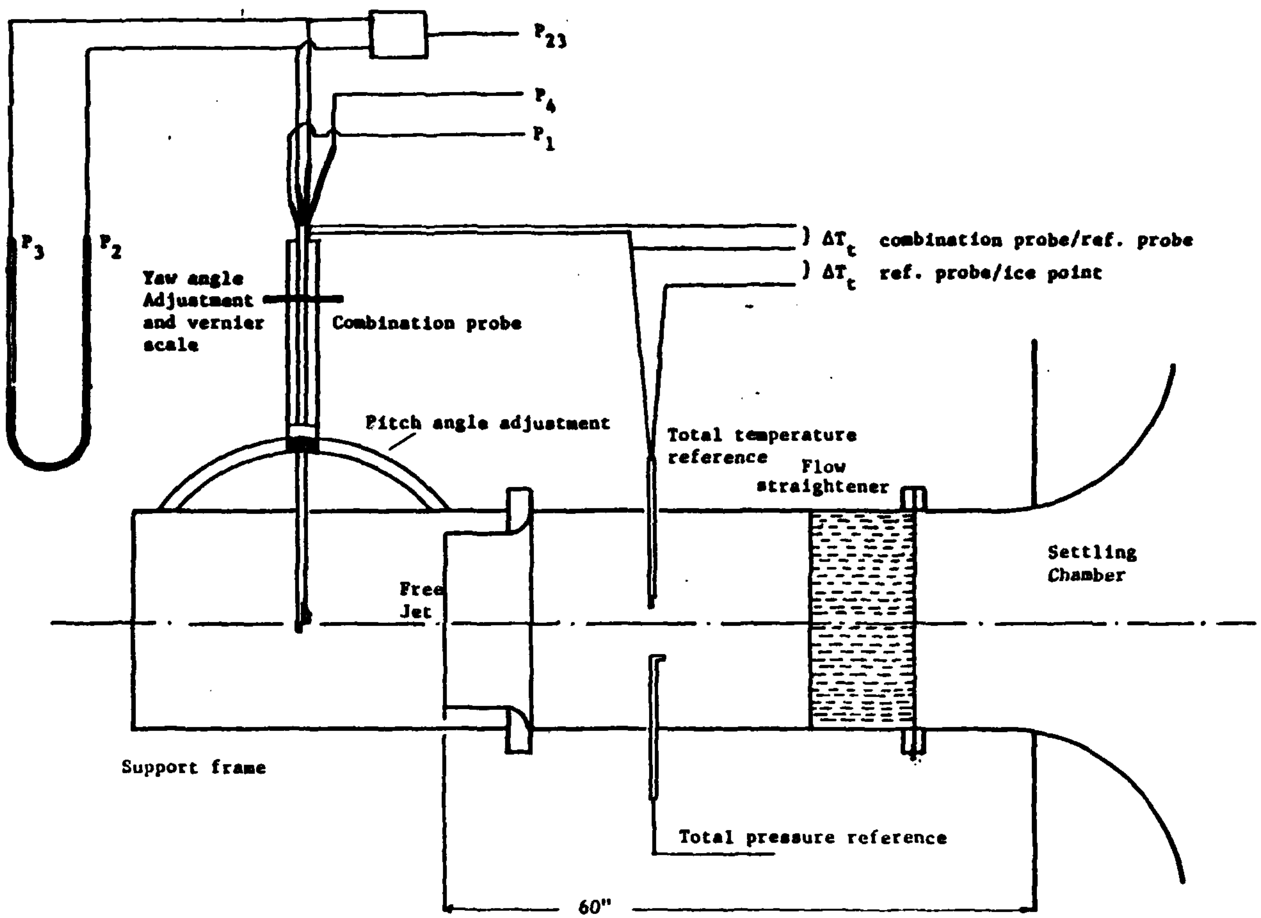


Figure 6. Calibration Facility Geometry (not to scale)

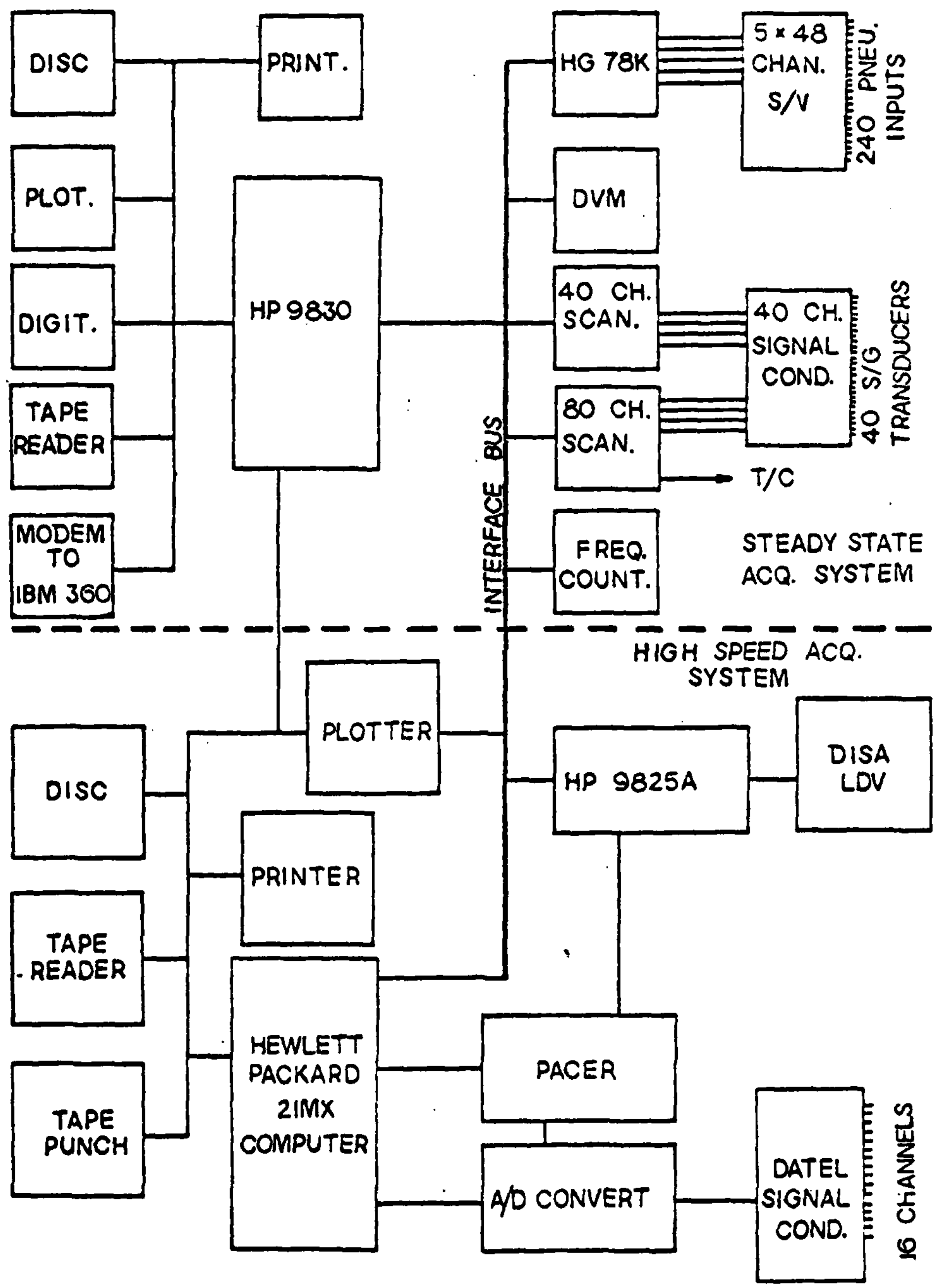


Figure 7. Data Acquisition System

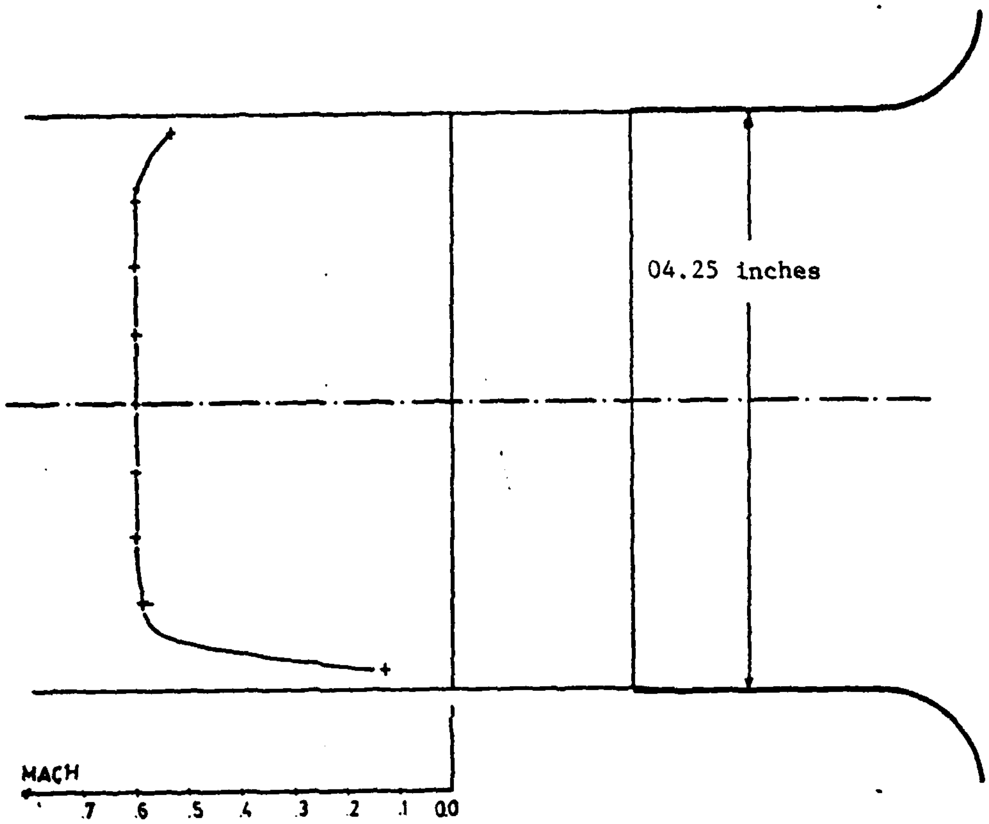


Figure 8. Velocity Distribution Measured Across the Jet

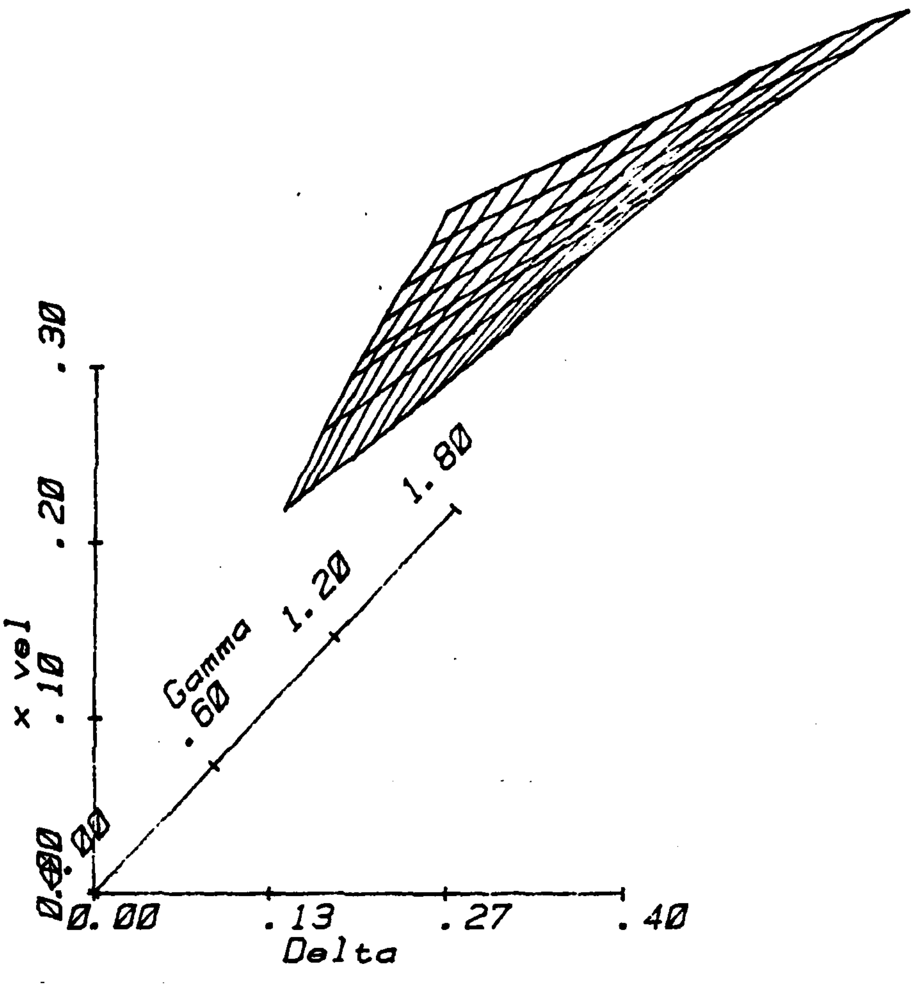


Figure 9. Surface Approximation for Dimensionless Velocity

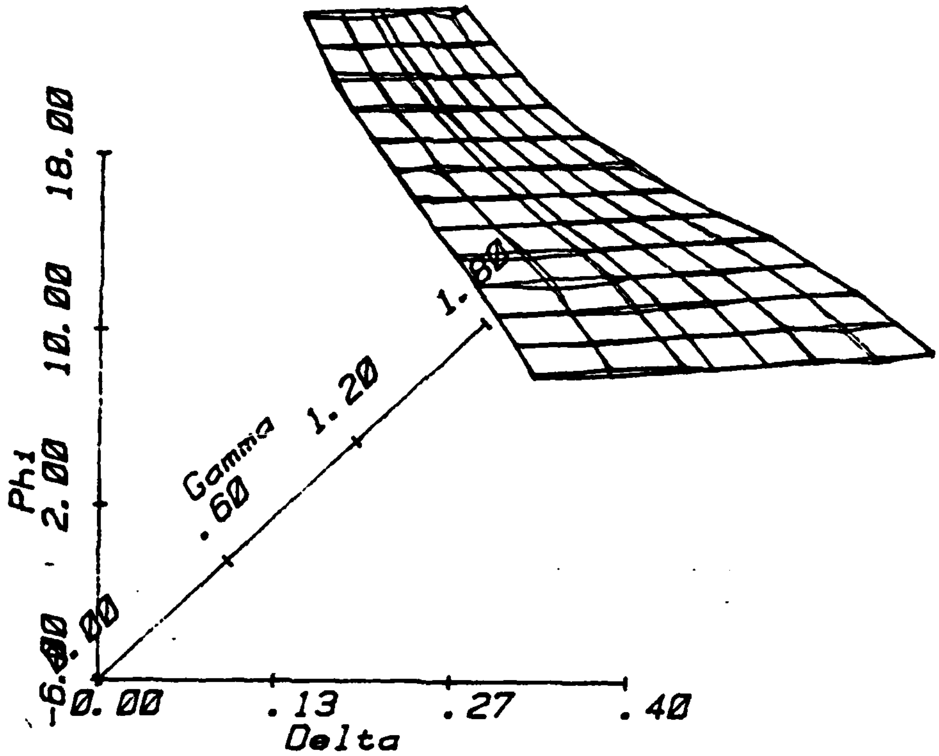


Figure 10. Surface Approximation for Pitch Angle

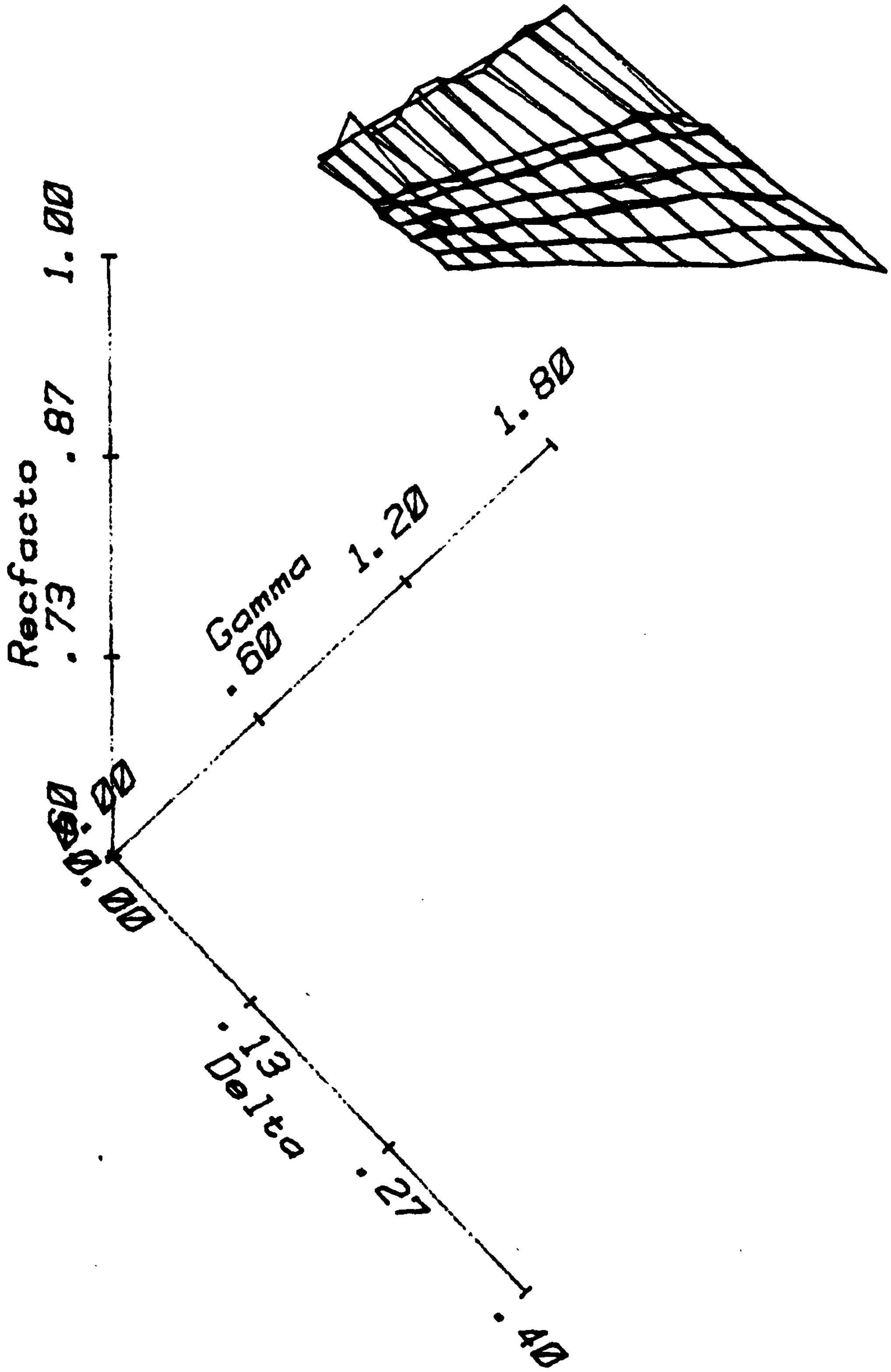


Figure 11. Surface Approximation for Temperature Recovery Factor

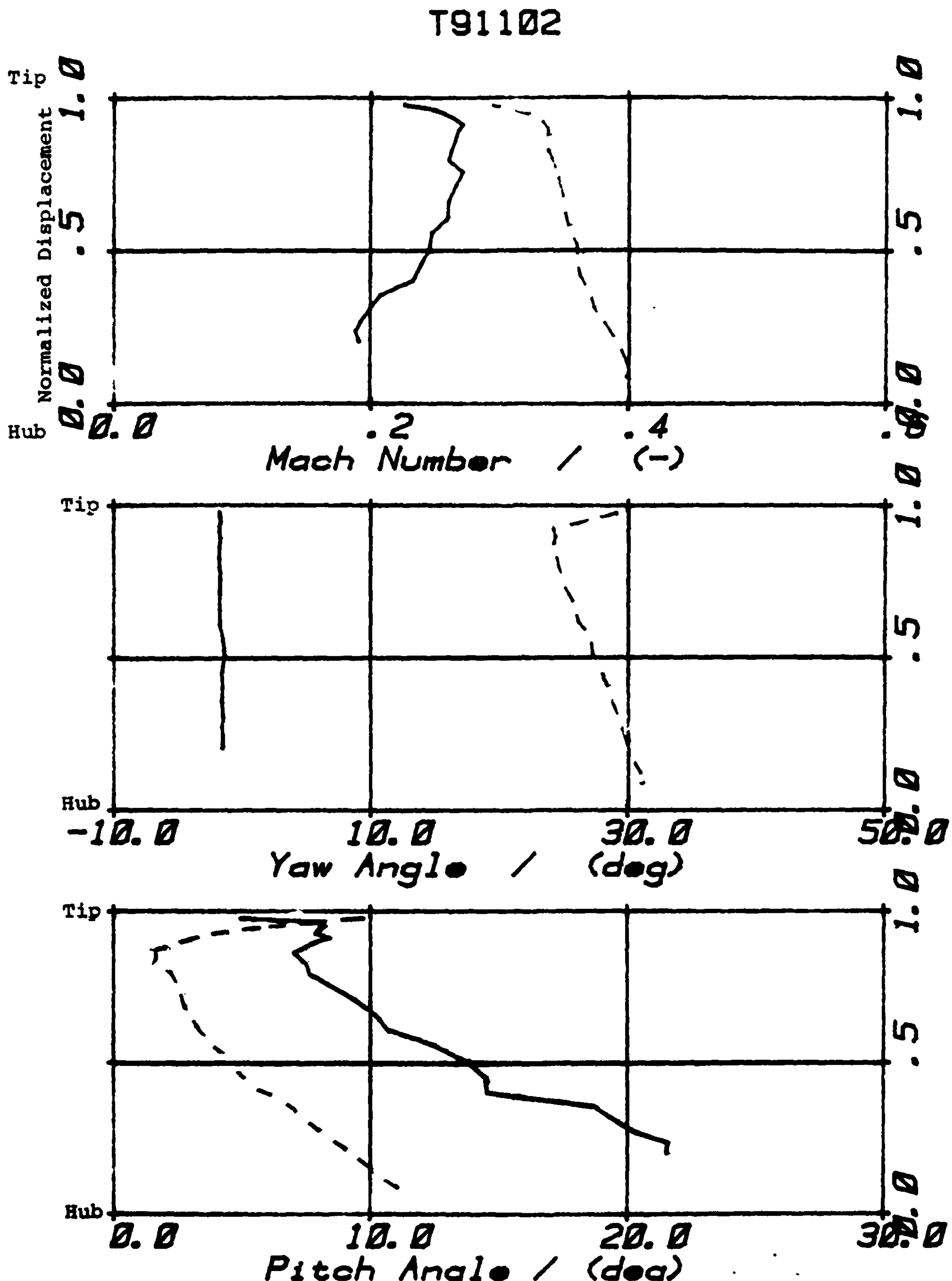


Figure 12. Results of Probe Surveys in the Compressor
——— Inlet, - - - - Outlet of Rotor

T91102

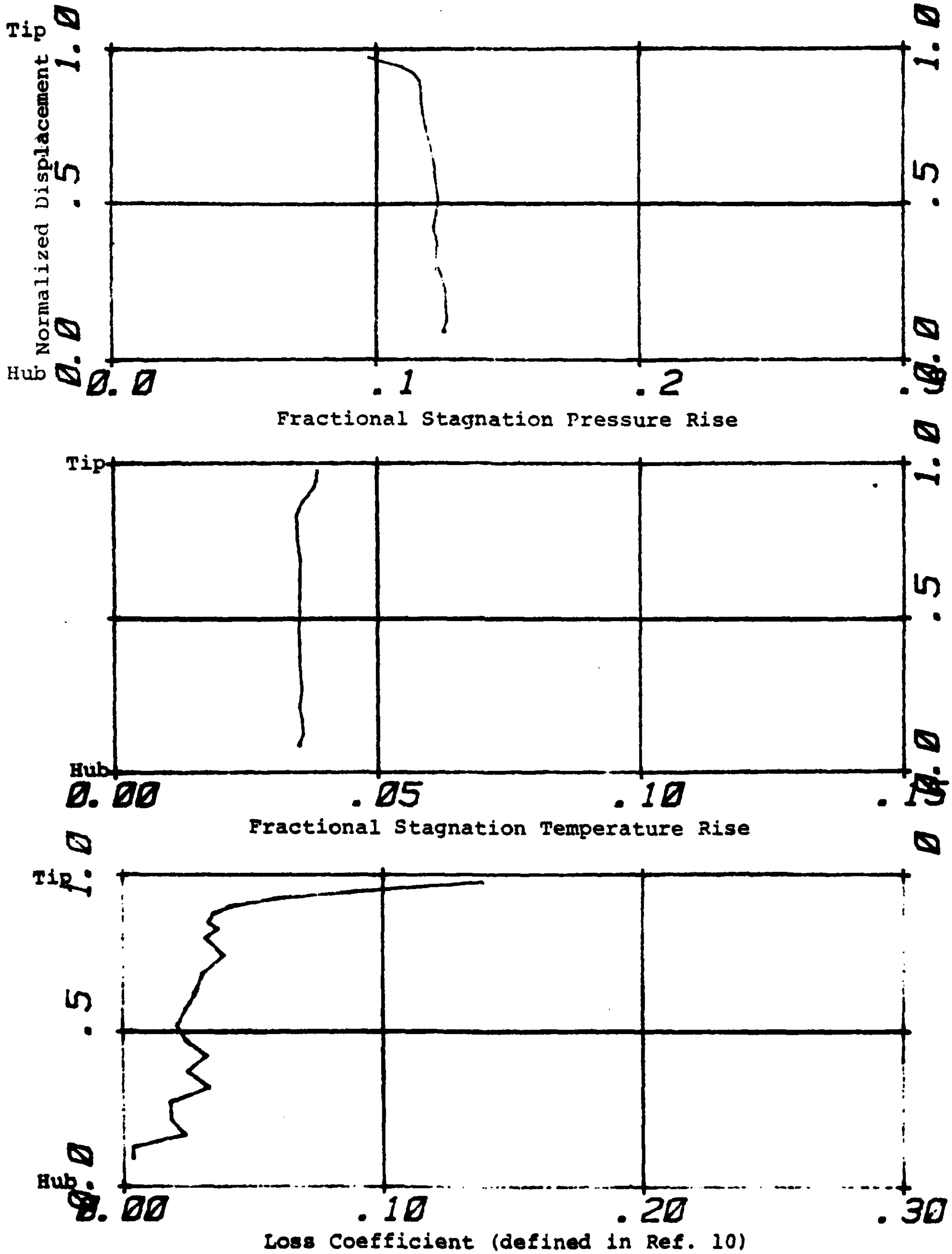


Figure 12 (Cont'd). Results of Probe Surveys in the Compressor

APPENDIX A. RELATIONSHIP OF PROBE PRESSURE TO FLOW VELOCITY AND ANGLE (by R. P. Shreeve)

A-1. Dimensionless Velocity and Mach Number

The velocity (V) can be made dimensionless by dividing by the "limiting" or "total" velocity (V_t) which, for a perfect gas is given by

$$V_t = \sqrt{2C_pT_t} \qquad A(1)$$

where T_t is the total temperature. V_t is the maximum steady velocity that the flow can have if the stagnation temperature remains unchanged since, by definition

$$C_pT_t = C_pT + \frac{V^2}{2} \qquad A(2)$$

and if the flow is accelerated to the limit of $T \to 0$, the velocity is that given by Equation A(1).

The dimensionless velocity obtained by dividing the velocity by its limiting value can be viewed as the "Fractional Velocity" or simply the "dimensionless velocity" and is here given the symbol X; thus

$$X = \frac{V}{V_t} \qquad A(3)$$

The relationship in Equation A(2) can be seen to give

$$\frac{T}{T_t} = 1 - X^2 \qquad A(4)$$

so that, using isentropic relationships, the ratio of the static (p) to total pressure (p_t) is given by

$$\frac{p}{p_t} = \left(\frac{T}{T_t}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 - X^2\right)^{\frac{\gamma}{\gamma-1}} \qquad A(5)$$

and static (ρ) to total density (ρ_t) is given by

$$\frac{\rho}{\rho_t} = \frac{p}{p_t}^{\frac{1}{\gamma}} = \left(1 - X^2\right)^{\frac{1}{\gamma-1}} \qquad A(6)$$

Using Equation A(2) and the definition of Mach number in a perfect gas, the relationship between the dimensionless velocity and Mach number can be shown to be

$$X^2 = \frac{\frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M^2} \qquad A(7)$$

or

$$\frac{\gamma-1}{2} M^2 = \frac{X^2}{1-X^2} \qquad A(8)$$

Clearly there is a non-linear but one-to-one relationship between X and M, so that if one is known so, uniquely, is the other. In compressor and turbine flows it is often more desirable to work with the dimensionless velocity, X, since it is directly proportional to the velocity itself until the stagnation temperature is changed, as across a rotor. The relationships in Equations A(4), A(5) and A(6) are also simpler than the corresponding expressions involving Mach number.

In representing the calibration of the probe, the dimensionless velocity, rather than Mach number, was used.

A-2. Probe Pressure Coefficients

The probe geometry is constant and when used is always adjusted so that the probe is aligned (in yaw) with the flow. Therefore, by dimensional analysis, the pressure coefficient, C_{p_n}, defined as

$$C_{p_n} = \frac{p_n - p}{\frac{\gamma}{2}pM^2} \qquad A(9)$$

where p_n is the pressure at sensor n, p and M are the static pressure and Mach number respectively of the oncoming flow, and γ is the ratio of specific heats, can be only a function of the Mach number, pitch angle (ϕ) and Reynolds Number (R_e), if a perfect gas and uniform flow are assumed.

As a consequence, the difference between the pressure coefficients at two sensors, m and n, defined as

$$C_{p_{mn}} = C_{p_m} - C_{p_n} = \frac{p_m - p_n}{\frac{\gamma}{2}pM^2} \qquad A(10)$$

must also be only a function of R_e, M and ϕ.

The Equation A(10) can be rewritten as

$$C_{p_{mn}} = \left(\frac{p_m - p_n}{p_m}\right)\cdot\left(\frac{p_m}{p_t}\right)\cdot\left(\frac{p_t}{p}\right)\cdot\left(\frac{2}{\gamma M^2}\right) \qquad A(11)$$

where p_t is the stagnation pressure. Using Equation A(5) and Equation A(8), Equation A(11) can be expressed as

$$C_{p_{mn}} = \left(\frac{p_m - p_n}{p_m}\right) \cdot \left(\frac{p_m}{p_t}\right) \cdot \frac{1}{\nu} \qquad \text{A(12)}$$

where ν is an explicit function of the dimensionless velocity (or Mach number); namely,

$$\nu = \left(\frac{\gamma}{\gamma-1}\right) X^2 \left(1 - X^2\right)^{\frac{1}{\gamma-1}} \qquad \text{A(13)}$$

Consequently, using Equation A(12), in general

$$\frac{p_m - p_n}{p_m} = \frac{C_{p_{mn}}}{(p_m/p_t)} \cdot \nu \qquad \text{A(14)}$$

where the quantities on the left hand side involve only the sensor measurements and where it is known that $C_{p_{mn}}$ depends on R_e, M (or X) and ϕ, and $\nu(X)$ is given explicitly by Equation A(13). From Equation A(9), Equation A(5) and Equation A(7) it must follow also that the ratio p_m/p_t depends only on R_e, M and ϕ

In principle, from an examination of Equation A(14), four independent sensors are necessary in order to calibrate a pressure probe uniquely for variations in M, R_e and ϕ. The present probe, when rotated to balance p_2 and p_3 (approximately) has only three independent measurements; namely, p_1, p_{23} and p_4, where p_{23} is the pneumatic average of the nearly-equal pressures p_2 and p_3. Only two independent parameters of the type in Equation A(14) can therefore be written. They are defined as

$$\beta = \frac{p_1 - p_{23}}{p_1} \qquad \text{A(15)}$$

and

$$\delta = \frac{p_1 - p_4}{p_1} \qquad \text{A(16)}$$

where an alternate for either one is obtained in the ratio

$$\gamma = \frac{\delta}{\beta} = \frac{p_1 - p_4}{p_1 - p_{23}} \tag{A(17)}$$

However, the geometry of the sensors is such that the effect of Reynolds number on the pressure coefficients should be extremely small in the range of Mach number of interest, and this has been verified experimentally (Reference 6). Therefore, in principle, calibration is required to establish the relationships

$$\beta = \beta(X,\phi) \tag{A(18)}$$

and

$$\delta = \delta(X,\phi) \tag{A(19)}$$

or

$$\gamma = \gamma(X,\phi). \tag{A(20)}$$

The selection of β, δ or γ is not arbitrary because it involves a selection between different sensitivities. For example, from Equation A(14)

$$\beta = \frac{p_1 - p_{23}}{p_1} = \frac{C_{p_{12}}}{(p_1/p_t)} \cdot \nu(X)$$

Since $C_{p_{12}}$ will probably not be strongly sensitive to Mach number, and (p_1/p_t) will be very close to unity for moderate pitch angles, β is a direct measure of the function $\nu(X)$ and therefore of the Mach number, with a second order dependence on pitch angle. In contrast

$$\delta = \frac{p_1 - p_4}{p_1 - p_{23}} = \frac{C_{p_{14}}}{C_{p_{12}}}$$

will not depend much on Mach number but, through $C_{p_{14}}$, because of the orientation of the sensors, will be highly sensitive to pitch angle. The quantity γ, given by

$$\gamma = \frac{p_1 - p_4}{p_1} = \frac{C_{p_{14}}}{(p_1/p_t)} \cdot \nu$$

will again be directly a measure of Mach number but, because of $C_{p_{14}}$, will also be strongly dependent on pitch angle.

APPENDIX B. DATA ACQUISITION AND REDUCTION

B-1. Data Acquisition Using BASIC Program AQCPRB

The data acquisition was carried out using a Hewlett Packard Model 9830A Calculator as controller. BASIC language program AQCPRB was written and stored on mass storage platter PL-001. A program listing is given in Section B-3.1.

The connections of the instrumentation shown in Figure 6 to the data acquisition system shown in Figure 7 are given in Table B-I. The data files containing the raw data stored on PL-001 are given in Table B-II.

B-2. Data Reduction Using FORTRAN Programs REST2 and COEFS

The data reduction was carried out using a Hewlett Packard Model HP21MX computer (Figure 7). First, the data files given in Table B-II were transferred to the HP21MX using the system utility FORTRAN program X9830 (stored on cartridge 28) on the HP21MX, and BASIC program 9830X on the HP9830A. The data file names were retained on the HP21MX.

Second, Program REST2 (cartridge 28) was used to collect the raw data files, reduce the data to pressure coefficients, temperatures and recovery factors, and then to store the reduced data in a single large data file CALNEW (on cartridge 28). The complete reduced data in CALNEW are shown in Table B-III and the listing of program REST2 is given in Section B-3.2.

The process of obtaining the coefficients of surface approximations to the calibration data was carried out using program COEFS (on cartridge 28) which is listed in Section B-3.3. The program reads the reduced data file CALNEW into an array. The surface approximation procedure is carried out for the dimensionless velocity X, the pitch angle, or the temperature recovery factor as required; one at a time. Whichever is required must be specified in all the statements which carry an asterisk in column #73. (In the listing in Section B.3.3 it is the pitch angle).

To output the plot correctly, the statements with asterisks in columns #73 and #74 must be edited to adjust the range of the Z-axis.

The order of the approximation is input by the operator and can be varied interactively up to an order of 6 for both independent variables. The coefficients for the approximations and the errors for each data point (see Equations 4, 5 and 10) are printed and plotted and the operator is asked for a name for the file in which to store the coefficients.

B-3. Program Listings

The following pages contain:

B-3.1 Basic Program ACQPRB

B-3.2 Fortran Program REST2

B-3.3 Fortran Program COEFS.

B-3.1. Basic Program AQCPRB

```
10 REM******AQCPRB*************************************
20 REM******ON-LINE DATA ACQUISITION PROGRAM***********
30 REM******FOR A COMBINATION  PROBE******************
40 REM
50 REM-- NOTE : THIS PROGRAM ONLY ACQUIRES THE RAW DATA,
60 REM--        MULTIPLIES IT WITH THE APPROPRIATE SCALING
70 REM--        FACTOR AND STORES IT.
80 REM
90 REM
100 REM
110 REM
120 REM
130 DIM A[14,12],B[3],A$[6],C$[20],R$[3],H$[3]
140 MAT A=ZER
150 DISP "ENTER NO. OF PITCH ANGLE(MAX.13)";
160 INPUT P9
170 FOR J=1 TO P9
180 DISP "ENTER PITCH ANGLE ("J")";
190 INPUT A[J,12]
200 REM
210 REM     DESCRIPTION:
220 REM       THIS SECTION PERFORMS SEQUENTIAL SCANNING
230 REM     OF SCANIVALVE 'V' BETWEEN PORT ADDRESSES SPECIFIED.
240 REM
250 REM     VARIABLES:
260 REM       V  = DESIRED S/V
270 REM       A1 = LOW PORT
280 REM       A2 = HIGH PORT
290 REM       P  = PRESENT S/V PORT
300 REM       S  = STEP SIZE
310 REM
320 REM     AUTHOR: R.N. GEOPFARTH,LT USN
330 REM     DATE:   FEB 79
340 REM
350 FORMAT B
360 FORMAT 2B
370 FORMAT 3B
380 FORMAT 4B
390 FORMAT F3.0
400 WRITE (13,380)256,20,768,512;
```

```
410 CMD "?D#","F1R7M3A0H0T3"
420 V=2
430 S=1
440 IF V#2 THEN 460
450 S=2
460 CMD "?D'"
470 WRITE (13,350)V;
480 WRITE (15,490)V
490 FORMAT "SCANIVALVE #",F3.0,/,/," PORT",8X,"VOLTAGE(UNCORR.)"
500 FOR A=2 TO 12 STEP S
510 GOSUB 1690
520 CMD "?D!"
530 WRITE (13,390)V+9
540 CMD "?D#","T3"
550 CMD "?C$"
560 ENTER (13,*)V0
570 WRITE (15,580)P,V0
580 FORMAT 1X,F3.0,4X,F12.6
590 K=A/S
600 REM  WRITE (15,610)K
610 REM   FORMAT 10X,"THIS IS K :",F6.2,/
620 A[J,K]=V0
630 CMD "?D!","C"
640 NEXT A
650 OUTPUT (13,380)256,20,768,512;
660 CMD "?D#","F1R7M3A1H1T3"
670 R=1
680 R$="?D!"
690 WRITE (15,700)R
700 FORMAT 5X,"SCANNER #",F2.0,/,2X,"CHAN",6X,"DATA"
710 B=25
720 S1=0
730 FOR L=1 TO 10
740 CMD R$
750 OUTPUT (13,390)B
760 CMD "?D#"
770 OUTPUT (13,370)256,8,512;
780 CMD "?C$"
790 ENTER (13,*)D1
800 S1=S1+D1
```

```
810 NEXT L
820 V=S1/10
830 WRITE (15,840)B,V
840 FORMAT 2X,F3.0,3X,F10.6
850 K=K+1
860 REM  WRITE (15,610)K
870 FORMAT 5X,/,/,F5.2
880 A[J,K]=V
890 CMD "?D(!","C"
900 H=2
910 H$="?D("
920 WRITE (15,700)H
930 FOR B=20 TO 23
940 S1=0
950 FOR L=1 TO 10
960 CMD H$
970 OUTPUT (13,390)B
980 CMD "?D#"
990 OUTPUT (13,370)256,8,512;
1000 CMD "?C$"
1010 ENTER (13,*)D1
1020 S1=S1+D1
1030 NEXT L
1040 V=S1/10
1050 WRITE (15,840)B,V
1060 K=K+1
1070 REM WRITE (15,610)K
1080 A[J,K]=V
1090 NEXT B
1091 CMD "?D(!","C"
1100 NEXT J
1110 GOTO 1120
1120 REM****DATA STORAGE*****
1130 PRINT
1140 PRINT
1150 DIM T$[15],U$[15],V$[15],W$[15],X$[15],Z$[15],O$[16],P$[16],Q$[16],Y$[16]
1160 DIM S$[16],N$[18]
1170 N$="  P BARO (INCH HG)"
1180 P$="     T PIPE(IP) "
1190 Q$="       T TUNNEL"
1195 Y$="      T JET(IP)"
1200 S$="D T(PIPE-COMB)"
```

```
1210 T$="    PA-PA "
1220 U$="   PCAL-PA**"
1230 V$="     P1-PA "
1240 W$="   P23-PA "
1250 X$="    P4-PA "
1260 Z$="   PK-PA "
1270 O$="          ** PHI "
1280 WRITE (15,1290)
1290 FORMAT 2X,"RAW DATA WITH VOLTAGE CORRECTED TO PRESSURES(IN.H2O)",/
1300 WRITE (15,1310)T$,U$,V$,W$,X$,Z$,N$
1310 FORMAT F10.0,F12.0,4F10.0,F18.0
1320 FOR J=1 TO P9
1330 A[J,1]=A[J,1]*100000
1340 A[J,2]=A[J,2]*100000
1350 A[J,3]=A[J,3]*100000
1360 A[J,4]=A[J,4]*100000
1370 A[J,5]=A[J,5]*100000
1380 A[J,6]=A[J,6]*100000
1390 A[J,7]=A[J,7]*10000
1400 WRITE (15,1410)A[J,1],A[J,2],A[J,3],A[J,4],A[J,5],A[J,6],A[J,7]
1410 FORMAT F10.4,F9.3," **",3F10.4,F9.3,F12.3
1420 NEXT J
1430 PRINT
1440 PRINT
1450 PRINT
1460 WRITE (15,1470)
1470 FORMAT 3X,"RAW DATA CORRECTED TO READINGS IN MILLIVOLTS",/
1480 WRITE (15,1490)Q$,P$,S$,Y$,O$
1490 FORMAT 5F16.0
1500 FOR J=1 TO P9
1510 A[J,8]=A[J,8]*1000
1520 A[J,9]=A[J,9]*1000
1530 A[J,10]=A[J,10]*1000
1540 A[J,11]=A[J,11]*1000
1545 A[J,12]=A[J,12]
1550 WRITE (15,1560)A[J,8],A[J,9],A[J,10],A[J,11],A[J,12]
1560 FORMAT 5F15.4
1570 NEXT J
1580 DISP "INPUT DATA FILE NAME D-----";
1590 INPUT A$
1600 FILES *
```

```
1610 ASSIGN A$,1,K
1620 MAT PRINT # 1;A
1630 IF END#1 THEN 1660
1640 PRINT "DATA STORED IN",A$
1650 END
1660 DISP "END MARKER READ";
1670 STOP
1680 REM*****************************************
1690 REM  SUBROUTINE "POSIT"
1700 GOSUB 1880
1710 D=A-P
1720 CMD "?D!"
1730 IF D<0 THEN 1760
1740 IF D>0 THEN 1810
1750 RETURN
1760 REM    HOME S/V
1770 WRITE (13,390)V+4
1780 WRITE (13,*)"C"
1790 WAIT 4000
1800 GOTO 1700
1810 REM     ADVANCE S/V
1820 FOR I=1 TO D STEP S
1830 WRITE (13,390)V-1
1840 WRITE (13,*)"C"
1850 WAIT 50
1860 NEXT I
1870 GOTO 1700
1880 REM     READ S/V ADDRESS
1890 CMD "?G$"
1900 P0=RBYTE13
1910 L=BIAND(P0,15)
1920 T=ROT(P0,4)
1930 M=BIAND(T,7)
1940 P=10*M+L
1950 WRITE (13,360)256,95;
1960 RETURN
```

B-3.2. Fortran Program REST2

```
&REST2 T=00004 IS ON CR00028 USING 00030 BLKS R=0000
      FTN4,L
            PROGRAM REST (3,99)
           *, Restore calibration data to new structure.
      C     ******************************************************************
      C     *                                                                *
      C     * RESTORES RAW CALIBRATION DATA FROM COMBINATION PROBE TO NEW    *
      C     * STRUCTURE.                                                     *
      C     *                                                                *
      C     ******************************************************************
            INTEGER IDCB(144),IFILE(3),ISIZE(2)
            INTEGER NOLF,NOCR(2),ICLR(3)
            REAL A(14,12)
            REAL GAMMA(16,16),DELTA(16,16),XVEL(16,16),PHI(16,16),RECF(16,16)
            DATA IDCBS  /144/
            DATA NOLF  /006537B/
            DATA NOCR  /000033B,040433B/
            DATA ICLR  /015524B,015515B,006537B/
        108 FORMAT (" ENTER FILE (XCPRB RAW DATA!"/
           *" DON'T FORGET SECURITY CODE & CARTRIDGE REFERENCE NUMBER!"/
           *"DCPRB :   :   "A2)
        109 FORMAT (" I   / J "12I6,A2)
        110 FORMAT ("  "I3,4X,F6.4,F6.3,4F6.4,F6.1,4F6.4,I6,A2)
        111 FORMAT (" OUTPUT INPUT DATA TO ANY OTHER DEVICE?  ENTER NO
           * OR LU# !"/"   "A2)
        112 FORMAT (" I   / J "12I10)
        113 FORMAT("  "I3,5X,F9.7,1X,F9.6,1X,4(F9.7,1X),F9.1,1X,4(F9.6,1X),I9)
        119 FORMAT (//1X"       Beta      Gamma       Delta       X vel
      $     Machno.        Phi     T Tunnel  T ref pipe  Tcombprobe
      $Rec.Fac")
        120 FORMAT (2X,10(F10.6,2X))
        121 FORMAT (//" REARRANGED DATA ARRAYS"/)
        122 FORMAT(" GAMMA("I2","I2")="F10.6"   DELTA("I2","I2")="F10.6" X VEL(
           *"I2","I2")="F10.6"  PHI("I2","I2")="F10.3" RECF("I2","I2")="F10.6)
        123 FORMAT (" MORE DATA YES OR NO "2A2)
        149 FORMAT ((3A2))
        151 FORMAT (3A2,1X,I2,1X,I2)
        161 FORMAT (I2)
        162 FORMAT (//" THE DATA FROM DATA SET #"I2" OF FILE "3A2" ARE
           *"/)
       1111 FORMAT ("Statement # "I6" Error # "I5" Encountered!")
            LI = LOGLU(ISESSN)
         77 WRITE (LI, 111) NOLF
            READ  (LI, 149) IDUM
            WRITE (LI, 149) (ICLR,I1=1,2)
            IF ( IDUM  .EQ.  2HNO ) GO TO 78
            CALL CODE
            READ  (IDUM,161) LO
            IF ( LO  .EQ.   1 ) GO TO 79
            IF ( LO  .EQ.   6 ) GO TO 79
            IF ( LO  .EQ.  18 ) GO TO 79
```

```
      GO TO 77
   78 LO = 0
   79 IF ( LO   .EQ.  LI ) LO = 0
      NMACH = 0
C     .....................................................................
C     .                                                                   .
C     .  PRESET NEW DATA ARRAYS.                                          .
C     .                                                                   .
C     .....................................................................
      DO 81 I=1,16,1
      DO 81 J=1,16,1
      GAMMA(I,J) = 0.
      DELTA(I,J) = 0.
      X VEL(I,J) = 0.
      PHI(I,J)   = 0.
   81 RECF(I,J)  = 0.
   80 NMACH = NMACH+1



C     .....................................................................
C     .                                                                   .
C     .  READ FILE DCPRB  FROM DISC INTO ARRAY A.                         .
C     .                                                                   .
C     .....................................................................
      WRITE (LI, 108) NOLF
      READ  (LI, 151) IFILE,ISECU,ICR
      IF ( ICR  .EQ.  0 ) ICR = 28
      IL = 336
      K1=1
      CALL OPEN  (IDCB,IERR,IFILE,IOPTN,ISECU,ICR,IDCBS)
      JJ = 11
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL RWNDF (IDCB,IERR)
      JJ = 12
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL READF (IDCB,IERR,A,IL)
      JJ = 13
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL CLOSE (IDCB,IERR,0)
      JJ = 14
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
```

```
C         ..............................................................
C         .                                                            .
C         .  OUTPUT INPUT DATA.                                        .
C         .                                                            .
C         ..............................................................
          WRITE (LI, 162) K1,IFILE
          IF ( LO  .NE.  0 ) WRITE (LO, 162) K1,IFILE
          WRITE (LI, 109) (J2,J2=1,12,1),NOLF
          IF ( LO  .NE.  0 ) WRITE (LO, 112) (J2,J2=1,12,1)
          DO 05 I1=1,14,1
          IF ( LO  .NE.  0 ) WRITE (LO, 113) I1,(A(I1,J2),J2=1,12,1)
       05 WRITE (LI, 110) I1,(A(I1,J2),J2=1,12,1),NOLF
          WRITE (LI, 119)
          IF ( LO  .NE.  0 ) WRITE (LO, 119)


C         ..............................................................
C         .                                                            .
C         .  DEFINE DELTA AND WRITE    ,   , X vel AND   INTO NEW ARRAY.  .
C         .                                                            .
C         ..............................................................
          NPITCH = 13
          DO 4712 J1=1,NPITCH,1
          B0 = (A(J1,3)-A(J1,4))/(A(J1,3)+30.0300*13.585-A(J1,1))
          G0 = (A(J1,3)-A(J1,5))/(A(J1,3)-A(J1,4))
          D0 = B0*G0
          X0=SQRT(1-(30.0300*13.585/(A(J1,6)+30.0300*13.585-A(J1,1)))**
         *(0.471.4))
          XM0 = SQRT((5*X0*X0)/(1-(X0*X0)))
          P0 = A(J1,12)
          TTUN = 32.6149+34.7279*A(J1,8)
          TREFP= 31.6149+30.6827*A(J1,9)-.3079*A(J1,9)*A(J1,9)
C         TREFJ= 31.6149+30.6827*A(J1,11)-.3079*A(J1,11)*A(J1,11)
          TCOMB= 31.6149+30.6827*(A(J1,9)+A(J1,10))-.3079*(A(J1,9)+
         *        A(J1,10))*(A(J1,9)+A(J1,10))
          R0   = 1 - ((TREFP-TCOMB)/(X0*X0*(TREFP+460)))
          WRITE(LI,120) B0,G0,D0,X0,XM0,P0,TTUN,TREFP,TCOMB,R0
          IF (LO .NE. 0)  WRITE(LO,120) B0,G0,D0,X0,XM0,P0,TTUN,TREFP,TCOMB,
         *R0
          GAMMA(NMACH,J1) = G0
          DELTA(NMACH,J1) = D0
          X VEL(NMACH,J1) = X0
          PHI(NMACH,J1)   = P0
          RECF(NMACH,J1)  = R0
     4712 CONTINUE
```

```
C       .............................................................
C       .                                                           .
C       .   OUTPUT NEW DATA ARRAY.                                  .
C       .                                                           .
C       .............................................................
        WRITE (LI, 121)
        I = NMACH
        DO 10 J=1,16,1
        IF ( LO  .NE.  0 ) WRITE (LO, 122) I,J,GAMMA(I,J),I,J,DELTA(I,J),I,
       *,J,XVEL(I,J),I,J,PHI(I,J),I,J,RECF(I,J)
   10   CONTINUE



C       .............................................................
C       .                                                           .
C       .   DECISION, WHETHER TO REARRANGE MORE FILES.              .
C       .                                                           .
C       .............................................................
        WRITE (LI, 123) NOCR
        READ  (LI, 149) IDUM
        IF ( IDUM  .EQ.  2HYE ) GO TO 80



C       .............................................................
C       .                                                           .
C       .   STORE NEW DATA ARRAY IN FILE CALNEW.                    .
C       .                                                           .
C       .............................................................
        IFILE(1)  = 2HCA
        IFILE(2)  = 2HLN
        IFILE(3)  = 2HEW
        ISIZE(1)  =   20
        ISIZE(1)  =  128
        ITYPE     =    1
        CALL CREAT (IDCB,IERR,IFILE,ISIZE,ITYPE,0,28,IDCBS)
        JJ = 15
        IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
        CALL OPEN  (IDCB,IERR,IFILE,IOPTN,0,28,IDCBS)
        JJ = 16
        IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
        CALL WRITF (IDCB,IERR,GAMMA,512,1)
        JJ = 17
        IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
        CALL WRITF (IDCB,IERR,DELTA,512,5)
        JJ = 18
        IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
        CALL WRITF (IDCB,IERR,XVEL,512,9)
```

```
      JJ = 21
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL WRITF (IDCB,IERR,PHI,512,13)
      JJ = 22
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR
      CALL WRITF (IDCB,IERR,RECF,512,17)
      JJ = 23
      IF ( IERR  .LT.  0 ) WRITE(1,1111) JJ,IERR
      CALL CLOSE (IDCB,IERR,0)
      JJ = 24
      IF ( IERR  .LT.  0 ) WRITE(1,1111)JJ,IERR

      WRITE (6,2345) IFILE
      DO 99  I=1,8,1
      WRITE(6,4567) I
   99 WRITE(6,3456) (GAMMA(I,J),DELTA(I,J),XVEL(I,J),PHI(I,J),RECF(I,J)
     * ,J=1,13,1)
 2345 FORMAT("  THESE ARE DATA FROM FILE :"3A2//"    GAMMA    DELTA
     *XVEL       PHI      RECF")
 3456 FORMAT(5(1X,F8.9))
 4567 FORMAT("  MACH NUMBER = "I3/)


      STOP 7777
      END
```

B-3.3. Fortran Program COEFS

```
&COEFS T=00004 IS ON CR00028 USING 00039 BLKS R=0000

FTN4,L
      PROGRAM COEFS (3,99)
C     ..................................................................
C     .                                                                .
C     .  This is program COEFS.                                        .
C     .  It approximates the reduced data from the calibration of      .
C     .  a combination probe with a calibration surface which is       .
C     .  expressed mathematically by high order polynominals for       .
C     .  both independed varibles.                                     .
C     .  The reduced data is read from file CALNEW and the coeffi-     .
C     .  cients resulting in the approximation are stored in a         .
C     .  file the operator assigns a name to.                          .
C     .                                                                .
C     ..................................................................
     *, CALCULATE CALIBRATION COEFFICIENTS.
      COMMON / AFLD / PLOTR
      COMMON / MATRX / A,B
      COMMON / SUMME / GAMMA,DELTA,PHI                                  *
      REAL PLOTR(256),A(49,49),B(49),COEFF(7,7)
      INTEGER IDCB(144),IFILE(3),ISIZE(2),NOCR(2),ICLR(3)
      REAL GAMMA(16,16),DELTA(16,16),XVEL(16,16),PHI(16,16),RECF(16,16)
      REAL R(16)
      DATA PI /3.141593/
      DATA IFILE /2HCA,2HLN,2HEW/
      DATA NOCR /000033B,040433B/
      DATA ICLR /015524B,015515B,006537B/
      DATA ISECU /0/
      DATA ICR   /28/
      DATA ITYPE /1/
      DATA ISIZE /1,128/

      DATA IDCBS /144/
  101 FORMAT (" ENTER ORDER M OF X - APPROXIMATION "2A2)
  102 FORMAT (" ENTER ORDER N OF Y - APPROXIMATION "2A2)
  103 FORMAT (" CHANGE # OF COEFF'S   ....   1"/
     *        " CHANGE ANGLE FOR AXES ....   2  "2A2)
  104 FORMAT (" ENTER ALPHAX, ALPHAY, X0 AND Y0")
  105 FORMAT (" ENTER FILE NAME FOR COEFFICIENT FILE: "3A2)
  106 FORMAT (3A2)
  149 FORMAT(""((3A2)))
  601 FORMAT (///" COEFFICIENTS FOR THE CALIBRATION SURFACE STORED IN FI
     *LE :"3A2/)
  602 FORMAT ((3X,16(6X,I2)))
  603 FORMAT (1X,I2,16(1X,F7.3)/3(3X,16(1X,F7.3)/))
  604 FORMAT (///"ERRORS(%)  AT EACH POINT"/)
  605 FORMAT ((3X,10(11X,I2)))
  606 FORMAT (1X,I2,7(2X,F11.6))
      LT = LOGLU(I)
```

```
C
C      ..................................................................
C      .  INITIALIZE PLOTTER AND DEFINE USER & PLOTTER AREAS.           .
C      .                                                                .
C      ..................................................................
       CALL INITG (13)
       XPMIN  = 0.
       XPMAX  = 10.
       YPMIN  = 0.
       YPMAX  = 10.
       ZPMIN  = 0.
       ZPMAX  = 10.



C
C      ..................................................................
C      .  X - AXIS :  DELTA                                             .
C      .  Y - AXIS :  GAMMA                                             .
C      .  Z - AXIS :  PHI OR XVEL OR RECF                               .
C      .                                                                .
C      ..................................................................
       XUMIN  = 0.000
       XUMAX  = 0.400
       YUMIN  = 0.000
       YUMAX  = 1.800
       ZUMIN  =      -6.0
       ZUMAX  =      18.0
       ALPHAX =     7.
       XA     = (XPMAX      -XPMIN      )/(XUMAX-XUMIN)
C      XB     = (XPMIN*XUMAX-XPMAX*XUMIN)/(XUMAX-XUMIN)

       XL     = (XPMAX      -XPMIN      )
       ALPHAY =  43.
       YA     = (YPMAX      -YPMIN      )/(YUMAX-YUMIN)
       YB     = (YPMIN*YUMAX-YPMAX*YUMIN)/(YUMAX-YUMIN)
       YL     = (YPMAX      -YPMIN      )
       ALPHAZ =  90.0
       ZA     = (ZPMAX      -ZPMIN      )/(ZUMAX-ZUMIN)
       ZB     = (ZPMIN*ZUMAX-ZPMAX*ZUMIN)/(ZUMAX-ZUMIN)
       ZL     = (ZPMAX      -ZPMIN      )
       XO     =  5.
       YO     =  5.
   85  PLOTR(61)  = (ALPHAX*PI)/180.
       PLOTR(62)  = (ALPHAY*PI)/180.
       PLOTR(63)  = (ALPHAZ*PI)/180.
       PLOTR(64)  = XO
       PLOTR(65)  = YO
       PLOTR(66)  = XA
       PLOTR(67)  = XB
       PLOTR(68)  = YA
       PLOTR(69)  = YB
       PLOTR(70)  = ZA
       PLOTR(71)  = ZB
```

```
      CALL SETSM (113,1.)
      CALL AXIS (XO,YO,XL,ALPHAX,8H Delta   , 8,XUMIN,XUMAX,4HF6.2,6,3)
      CALL AXIS (XO,YO,YL,ALPHAY,8H Gamma   ,-8,YUMIN,YUMAX,4HF6.2,6,3)
      CALL AXIS (XO,YO,ZL,ALPHAZ,9H Pitch    ,-8,ZUMIN,ZUMAX,4HF6.2,6,3) **


C     ..................................................................
C     .                                                                .
C     .  READ DATA FILE CALNEW.                                        .
C     .                                                                .
C     ..................................................................
      JJ = 1
      CALL OPEN (IDCB,IERR,IFILE,IOPTN,0,28,144)
      IF ( IERR  .LT.  0 ) WRITE(1,1001)JJ,IERR
      JJ = 2
      CALL READF (IDCB,IERR,GAMMA,512,LEN,1)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ = 3
      CALL READF (IDCB,IERR,DELTA,512,LEN,5)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ = 4
      CALL READF (IDCB,IERR,XVEL,512,LEN,9)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ =5
      CALL READF (IDCB,IERR,PHI,512,LEN,13)
      IF ( IERR  .LT.  0 ) WRITE(1,1001) JJ,IERR
      JJ = 6
      CALL READF (IDCB,IERR,RECF,512,LEN,17)
      IF ( IERR .LT. 0 ) WRITE(1,1001) JJ,IERR
      CALL CLOSE (IDCB,IERR,0)

C     DO 4321 I = 2,7,1                              NOTE: These statements can be
C     DO 4321 J = 1,13,1                                   used to exclude one or
C     GAMMA(I,J) = GAMMA(I+1,J)                            more machnumbers!
C     DELTA(I,J) = DELTA(I+1,J)
C4321 RECF (I,J) = RECF (I+1,J)

 1001 FORMAT ("  STATEMENT# "I5" ERROR # "F12.7" DETECTED")


C     ..................................................................
C     .                                                                .
C     .  PLOT CALIBRATION POINTS.                                      .
C     .                                                                .
C     ..................................................................
      NMACH = 8
      NPITCH = 13
      CALL SETSM (113,2.)
      DO 01 I=1,NMACH,1
      DO 01 J=1,NPITCH,1
      CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))           **
      IF ( J  .EQ.  1 ) CALL PLOT (XPLOT,YPLOT,2)
      IF ( J  .GT.  1 ) CALL PLOT (XPLOT,YPLOT,3)
```

```
C           WRITE(6,1234)DELTA(I,J),GAMMA(I,J),XVEL(I,J),RECF(I,J)
C1234 FORMAT("   DELTA="F9.6"  GAMMA="F9.6" XVEL="F6.2"   RECF="F9.6)
   01 CONTINUE
      DO 02 J=1,NPITCH,1
      DO 02 I=1,NMACH,1
      CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))              **
      IF ( I   .EQ.   1 ) CALL PLOT (XPLOT,YPLOT,2)
      IF ( I   .GT.   1 ) CALL PLOT (XPLOT,YPLOT,3)
   02 CONTINUE



C     .......................................................................
C     .                                                                     .
C     .  CALCULATE CALIBRATION SURFACE COEFFICIENTS.                        .
C     .                                                                     .
C     .......................................................................
      CALL SETSM (113,0.)
   91 WRITE (LI,101) NOCR
      READ  (LI,  *) MORDER
      IF (MORDER.GT.6) GO TO 87
   92 WRITE (LI,102) NOCR
      READ  (LI,  *) NORDER
      IF (NORDER.GT.6) GO TO 92
      M=MORDER+1
      N=NORDER+1
      CALL COMAT (A,B,M,N,NMACH,NPITCH)
      NEQUS=M*N
      CALL ELGJ (NEQUS)





      I1=0
      DO 93 I=1,M,1
      DO 93 J=1,N,1
      I1=I1+1
   93 COEFF(I,J)=B(I1)
      WRITE (LI,105)
      READ (LI,106) IFILE
      WRITE(LI,149) ICLR
      CALL CREAT (IDCB,IERR,IFILE,ISIZE,ITYPE,ISECU,ICR,IDCBS)
C     IF ( IERR   .GT.   0 ) STOP 0011
      CALL OPEN  (IDCB,IERR,IFILE,IOPTN,ISECU,ICR,IDCBS)
      IF ( IERR   .LT.   0 ) STOP 0012
      CALL WRITF (IDCB,IERR,COEFF,98)
      IF ( IERR   .LT.   0 ) STOP 0013
      CALL CLOSE (IDCB,IERR,0)
      IF ( IERR   .LT.   0 ) STOP 0014
      WRITE (6,601) IFILE
      WRITE (6,605) (J,J=1,N,1)
      DO 94 I=1,M,1
   94 WRITE (6,606) I,(COEFF(I,J),J=1,N,1)
      WRITE (6,605) (J,J=1,N,1)
```

```
C      ...................................................................
C      .                                                                 .
C      .  OVERWRITE DATA ARRAY WITH CALCULATED DATA                      .
C      .                                                                 .
C      ...................................................................
       WRITE (6,604)
       WRITE (6,602) (J,J=1,NPITCH,1)
       DO 20 I=1,NMACH,1
       DO 19 J=1,NPITCH,1
       SUM=0.
       DO 96 I1=1,M,1
       DO 96 J1=1,N,1
    96 SUM=SUM+(COEFF(I1,J1)*DELTA(I,J)**(J1-1))*GAMMA(I,J)**(I1-1)
C      R(J)=((XVEL(I,J)-SUM))/(XVEL(I,J))*100                              *
C      R(J)=((RECF(I,J)-SUM))/(RECF(I,J))*100                              *
       R(J)=  PHI (I,J)-SUM                                                *
C   19 XVEL(I,J)= SUM                                                      *
C   19 RECF(I,J)= SUM                                                      *
    19 PHI (I,J)= SUM                                                      *

    20 WRITE (6,603) I,(R(J),J=1,NPITCH,1)
       WRITE (6,602) (J,J=1,NPITCH,1)



C      ...................................................................
C      .                                                                 .
C      .  PLOT CALCULATED CALIBRATION SURFACE                            .
C      .                                                                 .
C      ...................................................................
       CALL SETSM (113,3.)
       DO 81 I=1,NMACH,1
       DO 81 J=1,NPITCH,1
       CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))            **
       IF (J.EQ.1) CALL PLOT (XPLOT,YPLOT,2)
       IF (J.GT.1) CALL PLOT (XPLOT,YPLOT,3)
    81 CONTINUE
       DO 82 J=1,NPITCH,1
       DO 82 I=1,NMACH,1
       CALL THRTW (XPLOT,YPLOT,DELTA(I,J),GAMMA(I,J),PHI(I,J))            **
       IF (I.EQ.1) CALL PLOT (XPLOT,YPLOT,2)
       IF (I.GT.1) CALL PLOT (XPLOT,YPLOT,3)
    82 CONTINUE


       IFILE(1) = 2HCA
       IFILE(2) = 2HLN
       IFILE(3) = 2HFW

```

```
C     ...............................................................
C     .
C     .  READ DATA FILE CALNEW.
C     .
C     ...............................................................
      CALL OPEN (IDCB,IERR,IFILE,IOPTN,0,28,144)
      IF ( IERR  .LT.  0 ) STOP 0001
      CALL READF (IDCB,IERR,GAMMA,512,LEN,1)
      IF ( IERR  .LT.  0 ) STOP 0002
      CALL READF (IDCB,IERR,DELTA,512,LEN,5)
      IF ( IERR  .LT.  0 ) STOP 0003
      CALL READF (IDCB,IERR,XVEL,512,LEN,9)
      IF ( IERR  .LT.  0 ) STOP 0004
      CALL READF (IDCB,IERR,PHI,512,LEN,13)
      IF ( IERR  .LT.  0 ) STOP 0005
      CALL READF (IDCB,IERR,RECF,512,LEN,17)
      IF ( IERR  .LT.  0 ) STOP 0006
      CALL CLOSE (IDCB,IERR,0)


C     ...............................................................
C     .
C     .  NEXT STEP?
C     .
C     ...............................................................
      WRITE (LI,103) NOCR
      READ  (LI,  *) IDUM
      IF (IDUM.EQ.1) GO TO 91
      IF (IDUM.EQ.2) GO TO 87
      CALL STOPG
      STOP 077
   87 WRITE (LI,104)
      READ  (LI,  *) ALPHAX,ALPHAY,X0,Y0
      GO TO 85
      END
```

TURBOPROPULSION LABORATORY

HP9830/21 MX Data Acquisition

Port/Channel Assignments

Test Probe Cal

Run No. ________

Date 6/12/81

New T.C. New dodge probe in 4 1/4" free jet--straight T_{Ref} Probe in pipe

	S.V. #1	S.V. #	SCANNER #1 ch	SCANNER #1	SCANNER #2 ch	SCANNER #2	SCANNER #3 ch	SCANNER #3
1			0		0		40	
2	PA - PA		1		1		41	
3			2		2		42	
4	Pcal - PA		3		3		43	
5			4		4		44	
6	P1 - PA		5		5		45	
7			6		6	T_{TUN} "J" IP	46	
8	P23 - PA		7		7	T_{TUN} "E" IP	47	
9			8		8	$\Delta T(T_{jet}-T_{pipe})$	48	
10	P4 - PA		9		9		49	
11			10		10	R7 x 10^3 = Mv	50	
12	Pt Tun - PA		11		11		51	
13			12		12		52	
14			13		13		53	
15			14		14		54	
16			15		15		55	
17	R7x10^5 = in H_2O		16		16		56	
18			17		17		57	
19			18		18		58	
20			19		19		59	
21			20		20		60	
22			21		21		61	
23			22		22		62	
24			23		23		63	
25			24		24		64	
26			25	P Baro	25		65	
27			26	R7x10^4=in Hg	26		66	
28			27	Abs.	27		67	
29			28		28		68	
30			29		29		69	
31			30		30		70	
32	Calib.		31	Calib.	31	Calib.	71	
33	inches H_2O		32	inches Hg	32	according	72	
34	≡ volts x 10^5		33	≡ volts x 10^4	33	to	73	
35			34		34	thermocouple	74	
36			35		35	type	75	
37			36		36		76	
38			37		37		77	
39			38		38		78	
40			39		39		79	
41								
42								
43								
44								
45								
46								
47								
48								

Measurements are in Volts

TPL 4/01/81
JH

Table B-I. Calibration Test Instrumentation Connections

File Name	Mach Number	Pitch Angle												
YPRB30	1	-6	-4	-2	0	2	4	6	8	10	12	14	16	18
YPRB40	2	"	"	"	"	"	"	"	"	"	"	"	"	"
YPRB45	3	"	"	"	"	"	"	"	"	"	"	"	"	"
YPRB50	4	"	"	"	"	"	"	"	"	"	"	"	"	"
YPRB55	5	"	"	"	"	"	"	"	"	"	"	"	"	"
YPRB60	6	"	"	"	"	"	"	"	"	"	"	"	"	"
YPRB65	7	"	"	"	"	"	"	"	"	"	"	"	"	"
YPRB70	8	"	"	"	"	"	"	"	"	"	"	"	"	"

Table B-II. Raw Data File Names

MACH NUMBER = 1

GAMMA	DELTA	XVEL	PHI	RECF
1.521552	.0812882	.1332521	-6.00000	.9917194
1.460870	.0773556	.1327658	-4.00000	.9884776
1.397380	.0736720	.1320334	-2.00000	.9915637
1.318777	.0695280	.1327658	0.000000	.9862901
1.254386	.0658292	.1327658	2.000000	.9791391
1.170305	.0617003	.1325223	4.000000	.9820595
1.100437	.0580034	.1325223	6.000000	.9916281
1.025862	.0547432	.1325223	9.000000	.9937222
.9521739	.0504077	.1322778	10.00000	.9789860
.8744588	.0465162	.1327658	12.00000	.9800366
.8034189	.0432724	.1330 9	14.00000	1.002970
.7531915	.0407311	.1332521	16.00000	.9840231
.7008547	.0377656	.1327658	18.00000	.9803300

MACH NUMBER = 2

GAMMA	DELTA	XVEL	PHI	RECF
1.535627	.1371644	.1763513	-6.00000	.8089528
1.487562	.1311814	.1768670	-4.00000	.8213995
1.420398	.1252310	.1768670	-2.00000	.7210634
1.359802	.1201603	.1761789	0.000000	.7959393
1.277915	.1128996	.1765233	2.000000	.7402264
1.182716	.1050076	.1765233	4.000000	.6759887
1.103961	.0978161	.1766954	6.000000	.6942834
1.012255	.0905588	.1768670	8.000000	.7305281
.9511002	.0852776	.1765233	10.00000	.6986769
.8725491	.0781117	.1766954	12.00000	.7744532
.8097562	.0728617	.1760063	14.00000	.7088474
.7628361	.0684725	.1770385	16.00000	.7349200
7094432	.0643027	.1760063	18.00000	.6128314

MACH NUMBER = 3

GAMMA	DELTA	XVEL	PHI	RECF
1.560976	.1880940	.2077222	-6.00000	.9853598
1.507067	.1791048	.2085493	-4.00000	.9934516
1.448028	.1696561	.2078605	-2.00000	.9965249
1.375000	.1616433	.2079984	0.000000	.9918246
1.289521	.1523746	.2078605	2.000000	.9923321
1.197158	.1414903	.2079984	4.000000	.9928216
1.116608	.1326734	.2078605	6.000000	.9912542
1.029982	.1226227	.2075839	8.000000	.9929143
.9543859	.1142000	.2081361	10.00000	.9884121
.8778360	.1056373	.2079984	12.00000	.9923444
.8124999	.0982455	.2084118	14.00000	.9945201
.7604167	.0919478	.2078605	16.00000	.9861048
.7137872	.0859320	.2082741	18.00000	.9880694

MACH NUMBER = 4

GAMMA	DELTA	XVEL	PHI	RECF
1.576802	.2075264	.2191589	-6.00000	.9960155
1.513386	.1981208	.2190310	-4.00000	.9908348
1.455272	.1878903	.2186459	-2.00000	.9955633
1.373206	.1776145	.2187743	0.000000	.9943811
1.285714	.1670249	.2191589	2.000000	.9965537
1.196172	.1547484	.2192869	4.000000	.9952673
1.113924	.1451374	.2194147	6.000000	.9903313
1.031496	.1350634	.2192869	8.000000	.9918269
.9527559	.1248047	.2189025	10.00000	.9911489
.8775511	.1153392	.2195426	12.00000	.9939903
.8159127	.1078667	.2191589	14.00000	.9882616
.7593751	.1002563	.2197979	16.00000	.9921843
.7138366	.0937518	.2187743	18.00000	.9845446

MACH NUMBER = 5

GAMMA	DELTA	XVEL	PHI	RECF
1.595331	.2448943	.2406194	-6.00000	.9954401
.538058	.2333929	.2402852	-4.00000	.9944553
.473545	.2216220	.2403966	-2.00000	.9966950
1.394422	.2088967	.2406194	0.000000	.9914392
1.300662	.1954783	.2405079	2.000000	.9900056
1.208719	.1821775	.2401736	4.000000	.9921237
1.119423	.1698332	.2407306	6.000000	.9945685
1.043081	.1588919	.2403966	8.000000	.9961605
.9595301	.1462810	.2402852	10.00000	.9942809
.8844156	.1355339	.2399504	12.00000	.9926516
.8223087	.1262552	.2403966	14.00000	.9966971
.7679338	.1178678	.2402850	16.00000	.9934781
.7148439	.1094591	.2398386	18.00000	.9896863

MACH NUMBER = 6

GAMMA	DELTA	XVEL	PHI	RECF
1.609131	.2783892	.2584729	-6.00000	.9956807
1.550336	.2665603	.2588692	-4.00000	.9940820
1.484055	.2506939	.2587702	-2.00000	.9945407
1.411968	.2361171	.2576768	0.000000	.9967434
1.315428	.2215773	.2585720	2.000000	.9970744
1.217540	.2057917	.2584729	4.000000	.9983823
1.126554	.1918572	.2578761	6.000000	.9965171
1.048533	.1787716	.2576768	8.000000	.9923269
.9672318	.1648825	.2578761	10.00000	.9940418
.8901345	.1528812	.2585718	12.00000	.9919972
.8234637	.1419061	.2587702	14.00000	.9947754
.7731843	.1332672	.2586711	16.00000	.9985398
.7170023	.1234930	.2579757	18.00000	.9911137

MACH NUMBER = 7

GAMMA	DELTA	XVEL	PHI	RECF
1.641706	.3195823	.2796194	-6.00000	.9996718
1.583654	.3039544	.2795326	-4.00000	.9973757
1.506256	.2881830	.2797930	-2.00000	.9979711
1.427875	.2704641	.2797064	0.000000	.9956771
1.329150	.2540321	.2798797	2.000000	.9960102
1.232625	.2356273	.2789234	4.000000	.9931526
1.146035	.2185309	.2793587	6.000000	.9932418
1.058027	.2019354	.2786617	8.000000	.9959774
.9731286	.1869960	.2785742	10.00000	.9957135
.8975096	.1728599	.2790977	12.00000	.9935628
.8358778	.1616661	.2797930	14.00000	.9932035
.7793496	.1507600	.2786617	16.00000	.9940710
.7320075	.1427365	.2801394	18.00000	.9941336

MACH NUMBER = 8

GAMMA	DELTA	XVEL	PHI	RECF
1.654221	.3595260	.3001155	-6.00000	.9980165
1.596867	.3415878	.3005725	-4.00000	.9977407
.530151	.3221327	.3004204	-2.00000	1.000791
.444632	.3014336	.2997335	0.000000	.9969914
1.349627	.2864642	.3004204	2.000000	.9952534
1.247492	.2629735	.2993505	4.000000	.9952784
1.156040	.2430088	.2997335	6.000000	.9948375
1.072148	.2253740	.2991971	8.000000	.9948773
.9815592	.2067599	.2995806	10.00000	.9960829
.9019120	.1913724	.3000392	12.00000	.9951346
.8399669	.1787676	.3000390	14.00000	.9957010
.7812500	.1675020	.2995039	16.00000	.9938134
.7248764	.1554063	.2998099	18.00000	.9951300

Table B-III. Reduced Calibration Data

APPENDIX C. CHROMEL-CONSTANTAN THERMOCOUPLE OUTPUT APPROXIMATION

The relationship between the millivolt output of the Type E (Chromel-Constantan) thermocouple element and the temperature is given by the manufacturer (Omega Engineering, Inc., P.O. Box 4047, Stamford, Connecticut, 06907) from NBS Standard tables. For a range of 0° to 170° Fahrenheit the temperature as a function of the voltage was approximated by a second order polynomial using the method of least squares. Figure C1 shows the approximation together with the coefficients for the curve. The second order approximation in Figure C1 was used in the data reduction programs for the probe.

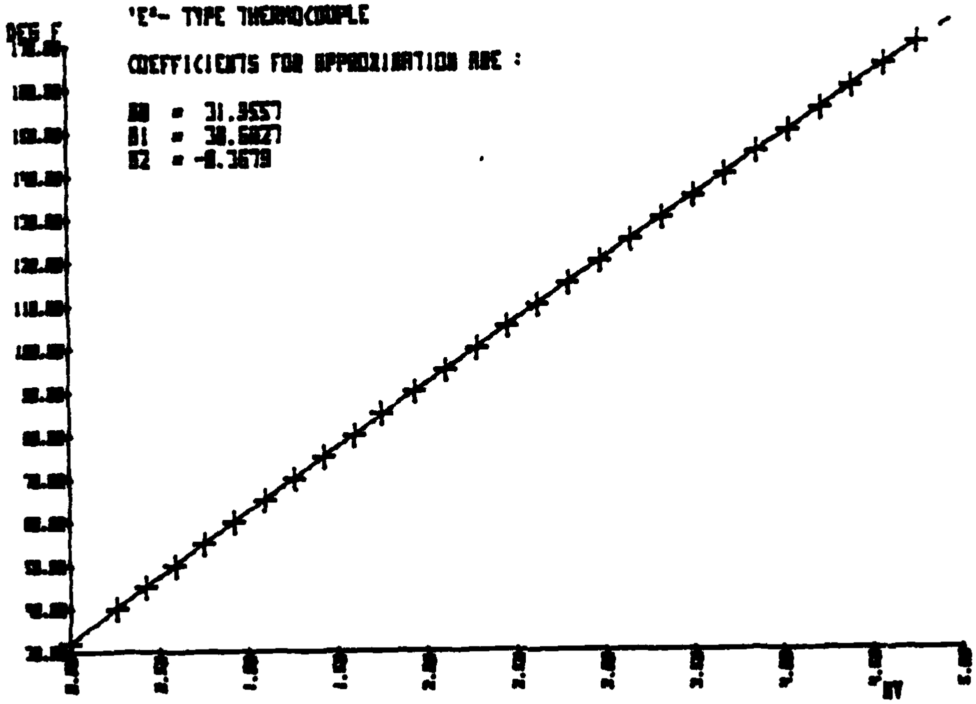


Figure C1. Chromel-Constantan Thermocouple Voltage Output vs Temperature

APPENDIX D. PNEUMATIC AVERAGING OF UNSTEADY PRESSURES

Other investigators have questioned whether a pneumatic probe measures the correct time average value of the impact pressure in an unsteady flow (References 7 and 8). It is clear that the possible error in the probe measurement will depend on the relationship between the average pressure level and the unsteady departures therefrom. Weyer, in Reference 7, has measured the magnitude of the error for a particular wave form. In order to get an idea of the error which might be involved if the measurement of P1 was taken to be the time-averaged total pressure, the unsteady pressure distribution in the measuring plane of the probe was observed in the compressor. Figure D1 shows the pressure distribution measured behind the compressor rotor using a simple impact pressure probe incorporating a Kulite semiconductor transducer at the tip. Rotor rotational speed was 15,200 rpm, resulting in a (blade-passing) frequency of 4.56 Khz in the pressure variation. Using the notation of Reference 7, the characteristics of the signal were determined to be the following:

Time average value of the pressure, $\bar{P}_1 = 434'' H_2O$

Peak-to-peak amplitude of the pressures,

$(P_{max} - P_{min}) = 2P1_a = 16'' H_2O$

Ratio of wave amplitude to mean value, $\frac{2P1_a}{\bar{P}_1} = 0.037$

Figure D2 (from Reference 7) shows the relationship between the error which was measured for a particular pneumatic probe, the frequency, the pressure level and the amplitude of the pressure changes for the particular wave shape indicated in the figure. It is observed that the frequency involved in the present measurements exceeds the range given in Figure D2, and that the value of $2Pl_a/\bar{P}_1$ was also very much smaller.

Similar comparisons between the pressure readings P2 and P3 and corresponding Kulite probe measurements showed that for these sensors $2Pl_a/\bar{P}_1$ was even smaller, thus any error in the averaging of P2 and P3 should be negligible.

An equivalent Kulite probe for P4 did not exist, so that a comparison for this sensor could not be made. However, since the tube for P4 is inclined at an angle to the flow comparable to those of P2 and P3, it can reasonably be assumed that the conclusions are similar.

For operating conditions at higher speeds and flow rates, the above conclusions must be reexamined for the time-varying rotor exit conditions then measured. Whereas the data in Figure D2 suggest that the error becomes small at higher frequencies, it was shown in Reference 9 that measurable errors could occur at 3 - 8 Khz in particular pneumatic systems if the wave form was sufficiently extreme (implying large values of the parameter $2Pl_a/\bar{P}_1$).

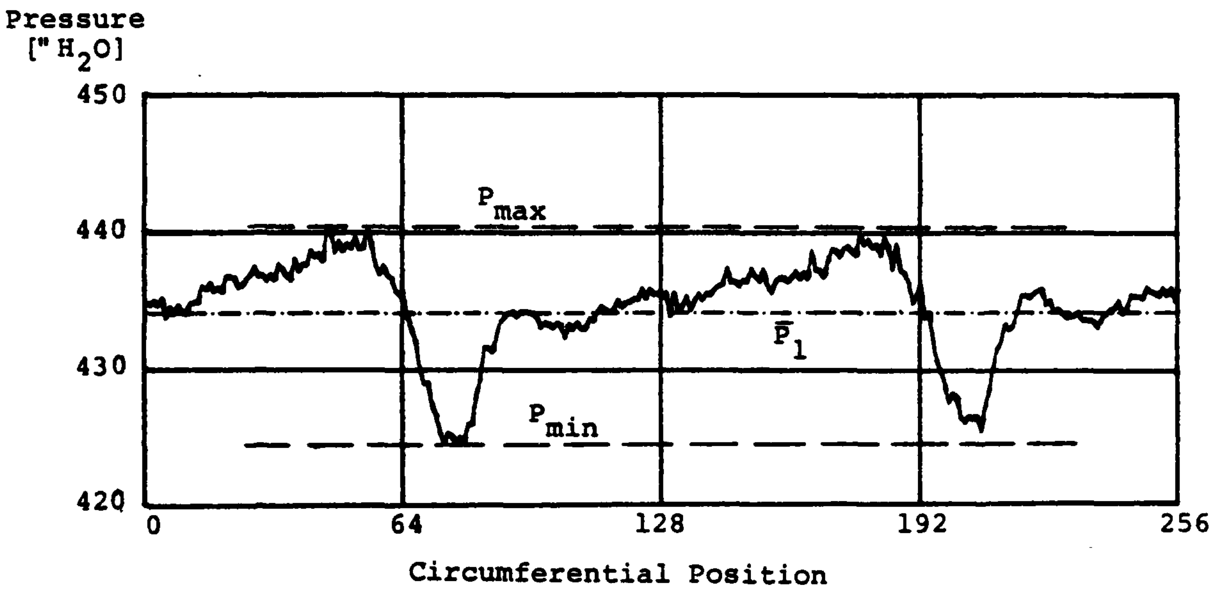


Figure D1. Kulite Probe Measurement of the Pressure Seen by the P1 Sensor at the Rotor Exit

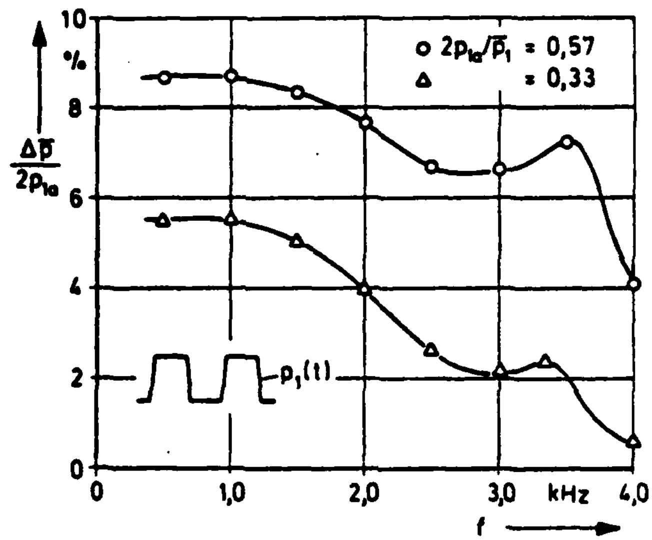


Figure D2. Relative Error in the Pressure Measurement Using Conventional Pneumatic Measurement Systems Depending on the Frequency for Two Different Pressure Amplitudes (measurement hole diameter: 0.028", sharp edge)

(Reproduced from Ref. 7.)

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